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Technical Report

No. 13162

STUDY AND ANALYSIS OF HEATING CONCEPTS FOR MILITARY GROUND VEHICLES

CONTRACT NUMBER DAAE07-85-C-R167

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GLOBAL THERMOELECTRIC POWER SYSTEMS LIMITED
P.O. BOX 400
BASSANO, ALBERTA, CANADA T0J 0B0

U.S. ARMY TANK-AUTOMOTIVE COMMAND
RESEARCH, DEVELOPMENT & ENGINEERING CENTER
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B. M. Jatzeck and D. K. Marling

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A 7-month study of state-of-the-art non-turbine heating concepts was conducted and completed by Global Thermoelectric Power Systems Ltd. of Bassano, Alberta, Canada. One preferred concept and one alternative were selected and examined. A multifueled heater system suitable for use in current and future military and commercial ground vehicles based on the preferred concept was designed and developed to Level 1 detail.

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SUMMARY

The heaters currently used by the U.S. Army for their ground vehicles exhibit a number of deficiencies. They are known to be unreliable in operation and require frequent maintenance. In addition to this, several different models are being used, each of which require their own set of spare parts. As a result, the U.S. Army Tank-Automotive Command has begun a program to replace these heaters with standardized units that offer improved reliability and self-sustained operation.

One requirement is that the heaters use technology which is suitable for current and future military ground vehicles. It was for this purpose that the U.S. Army Tank-Automotive Command had awarded Contract Number DAAE07-85-C-R167.

A study of a number of state-of-the-art fuel-fired heating concepts was conducted and completed. Several methods of directly converting heat into electricity and of atomizing liquid hydrocarbon fuels were examined and compared. The most suitable means of power generation was found to be the thermoelectric converter, while the ultrasonic atomizer and return-flow nozzle were selected for handling liquid fuels. A design for a modular multifueled system for personnel heating, vehicle engine preheating, and portable heating based on the thermoelectric converter and ultrasonic atomizer was completed and is presented.

The discussion of this report (Section 5.0.) contains the study and analysis of the direct energy converters and liquid fuel atomizers. A description of the final choices is included as well. The remainder of this section consists of the design based upon the preferred choice and a description of the various subsystems. A cost estimate for the heater system is presented at the conclusion of this report.

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PREFACE

This report was prepared by Global Thermoelectric Power Systems Ltd. of Bassano, Alberta, Canada under U.S. Army Tank-Automotive Command Contract DAAE07-85-C-R167.

The Tank-Automotive Command Systems Laboratory's Tactical Systems Support Division was responsible for contract management, with Mr. Raymond M. Womack, AMSTA-RCC, as the technical representative for the contracting officer. Additional assistance was provided by Mr. Mohsin Singapore and Mr. Gerald Schuetz, U.S. Army Tank-Automotive Command.

No classified information is contained in this report.

No technical information appearing in this report or the accompanying drawings was formulated at Global's expense.

The authors gratefully acknowledge the contributions of a number of their fellow employees throughout the course of the contract, as well as the assistance provided by the various individuals contacted with respect to information required in the preparation of the monthly and final reports.

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1.0. INTRODUCTION

The following report was prepared by Global Thermoelectric Power Systems Ltd. of Bassano, Alberta, Canada under U.S. Army Tank-Automotive Command Contract Number DAAE07-85-C-R167. It documents the survey of a number of state-of-the-art heating concepts (other than turbine) and the development of a multifueled heater system based on the one best suited for application to current and future military ground vehicles. The resulting system consists of an interchangeable heat and power module (HPM) to provide heat and power, a personnel heat exchanger, a coolant heat exchanger, and a portable heat exchanger. It is designed to replace heaters which are currently in place and used for those same applications.

In addition to this investigation, analysis, and comparison, it was required that reports and Level 1 drawings be provided by Global. These documents will then be utilized at some future date to develop a comprehensive data package for such a heater system.

2.0. OBJECTIVES

The objectives of work done under contract number DAAE07-85-C-R167 were to:

- Study and analyze a number of state-of-the-art heating concepts other than turbomachinery.
- Determine their applicability to current and future military ground vehicles.
- Recommend and develop one concept which meets the requirements outlined in U.S. Army Tank-Automotive Command Solicitation Number DAAE07-85-R-R036.
- Present data and documents supporting the recommendation.

3.0. CONCLUSIONS

The authors of this report conclude that:

- The thermoelectric converter is, of all the electrical power generation methods considered, the best suited for the heater system, meeting all the technical requirements and being the most cost-effective.
- The ultrasonic atomizer is the best method of conditioning liquid hydrocarbon fuels prior to combustion and is suited for the heater system.
- The return-flow nozzle is a suitable alternative to the ultrasonic atomizer in liquid fuel combustion.

- The heater system, as conceived and designed, is suited for further development, meeting all of TACOM's technical requirements.

4.0. RECOMMENDATIONS

The authors of this report recommend that:

- Development of the heater system, as proposed, be continued as proof of concept, which would include detailed design and design modification.

- A working prototype of the heater system be constructed and tested, incorporating any changes arising from the detailed development phase and prototype testing.

- A working prototype of the heater system on which development, testing, and modification have been completed be presented to TACOM for field testing and evaluation.

5.0. DISCUSSION

5.1. Survey of State-Of-The-Art Technologies

5.1.1. General. It was required that the heater operate with no external electrical power after startup and that it be capable of burning the following liquid fuels over the given temperature ranges:

• DF-2, F-54	0°F - +70°F
• DF-1	-25°F - 0°F
• DF-A	-65°F - -25°F
• JP4, JP5	-65°F - +70°F
• MOGAS	-65°F - +70°F
• Gasoline (automotive, leaded and unleaded)	-65°F - +70°F

A survey of methods to accomplish these tasks was conducted, emphasizing techniques for generating electricity directly from a heat source, as well as methods of burning the aforementioned fuels.

5.1.2. Literature Survey. A search of several computer data bases was conducted by Global Thermoelectric at the facilities of the Alberta Research Council Industrial and Engineering Research Division in Edmonton, Alberta, Canada.

The following data bases were accessed:

- NTIS - National Technical Information Service (U.S. Government Publications).
- Compendex - Engineering Information Inc.
- SAE - Society of Automotive Engineers.
- COLD - Cold Regions Data Base.
- WPI - Patents (1963-1980).
- WPI Latest - Patents (1981-Present).
- INSPEC - Information Services for the Physics and Engineering Communities.
- PTS - Defense Markets and Technology.

The search strategy consisted of entering appropriate keywords when prompted by the computer and checking the number of references pertaining to them. Initially, the search concentrated on topics that were specifically applicable to the project, becoming more general when nothing was available or what was found was unrelated. The latter approach was used towards the end of the session in order to save time and allow access to as many data bases as possible.

Not all the titles in a given category were sought, as often there would be a large number available in a particular data base. In these instances, those dated 1980 and onwards were selected for further examination.

Several hundred titles in the areas of direct energy conversion and combustion were obtained. They covered not only the theoretical aspects of these two fields but also their current stage of development. They were reviewed to select suitable subjects for analysis and comparison. A number of these titles were examined further, and are listed in the Appendix. Some of them were used for this report.

5.1.3. Direct Energy Converters. The area of direct energy converters has been, and still is being actively researched, which was reflected by the large number of articles that were found during the data base search, as shown in the Appendix.

Seven possible candidates for the electrical generator were found in the literature. These were:

- Thermoelectrics[1,2].
- Thermionics[1,3].

- Thermophotovoltaics[1,4,5].
- Sodium heat engine[6,7].
- Magnetohydrodynamics[1,8,9].
- Thermomagnetics[10,11].
- Thermally regenerative electrochemical systems[12].

5.1.4. Liquid Fuel Atomizers. The subject of liquid fuel combustion was also one of active investigation, as a number of methods exist by which this can be done. It should be emphasized that any liquid fuel burner is dependent upon the condition of the fuel prior to combustion. That is to say, the performance is affected by the degree and quality of atomization or vaporization that the fuel undergoes before ignition. Any fuel that is still liquid prior to combustion will not burn quickly, which results in inefficient combustion, characterized by unburned fuel and soot. Therefore, the effectiveness of the entire heater system is largely dependent on the atomizer.

There are 10 atomizing techniques which are being investigated. These are:

- Simplex nozzle[13,14,15].
- Return flow nozzle[13,16,17,18].
- Electric nozzle preheater[16,19].
- Air atomizer[16,20].
- Electrostatic atomizer[21].
- Fuel vaporizer[22].
- Rotary burner[23].
- Catalytic burner[24,25].
- Ultrasonic atomizer[16,26].
- Pulse burner[27,28].

5.2. Principles of Operation

5.2.1. General. In determining the technical suitability of a particular direct energy converter (DEC) or a liquid fuel atomizer for use in the heater system, an understanding of the operating principles can help in ascertaining whether or not it can be applied for this purpose.

5.2.2. Direct Energy Converters.

5.2.2.1. Thermoelectrics. A thermoelectric DEC generates voltage across an electrical circuit consisting of two semiconductors or dissimilar metals[1]. This is possible if the junctions between the materials have different temperatures.

The open-circuit voltage is defined as [2]:

$$V = S\,(T_H - T_C),$$

where:

V = generated voltage,
S = Seebeck coefficient,
T_H = hot junction temperature,
T_C = cold junction temperature.

The Seebeck coefficient is a property of the thermoelectric materials[29].

5.2.2.2. Thermionics. A thermionic converter has a heated cathode which emits electrons[1,3]. These electrons move across a small gap to a cooler anode, and are returned to the cathode by means of an external electrical circuit. This gap is either a vacuum or filled with a conducting medium, such as cesium vapour[29,30]. There does not appear to be any means by which the converter performance can be mathematically estimated, as this appears to be largely dependent upon the ability of the cathode material to emit electrons.

5.2.2.3. Thermophotovoltaics. An emitter is heated to a temperature at which it emits photons, which are converted into electricity by photocells[1,4,5]. The effectiveness of this converter is dependent upon the photon wavelength (determined by the emitter material and temperature)[4,31] and the type of photocell used[4,5].

The output power is [5]:

$$P = JVA,$$

where:

P = output power (at maximum power),
J = photocell current per unit area (at maximum power),
V = photocell voltage (at maximum power),
A = photocell array area.

5.2.2.4. Sodium heat engine. References for this are found in [6,7]. A sealed vessel containing liquid sodium is divided into low and high pressure sections by a tube of beta"-alumina (which is covered by a porous electrode) and a liquid metal pump.

The temperature of the outer region is lower than that of the inner one. A sodium vapour pressure differential across the beta"-alumina arises from this difference in temperatures.

The liquid sodium is in the high-pressure, high-temperature section. Sodium ions enter the beta"-alumina and move through it due to the difference in pressures. The electrons pass through an external circuit and recombine with the ionized sodium at the porous electrode. The sodium then vapourizes at the high temperature and low pressure, moves to the outer section, and is condensed. It returns to the pool by means of the pump.

The open circuit voltage is given by [7]:

$$V = \frac{RT_2}{F} \ln \left[\frac{P_V(T_2)}{(T_2/T_1)^{1/2} \, P_V(T_1)} \right] ,$$

where:

V	= open circuit voltage,
R	= gas constant,
F	= Faraday's constant,
T_1	= condensation temperature,
T_2	= evaporation temperature,
$P_V(T_1)$, $P_V(T_2)$	= sodium vapour pressures at T_1, T_2, respectively.

5.2.2.5. Magnetohydrodynamics. A fluid, which is electrically conductive, flows perpendicularly through a magnetic field[1,9]. This creates an electric field perpendicular to both the direction of fluid flow and the magnetic field. A pair of electrodes aligned perpendicular to the electric field and parallel to the fluid flow and magnetic field directions will facilitate current flow if connected in a circuit with an external electrical load.

Two magnetohydrodynamic (MHD) methods appear to exist: liquid metal MHD and plasma MHD[9]. In the former, a gas containing liquid metal is used[9], while for the latter, a high-temperature plasma is the fluid[1,9]. The plasma MHD generators may "seed" the plasmas with material to increase the conductivity to a level suitable for power generation[9,32].

One expression for the power output of the generator is [9]:

$$P = EJAx,$$

where:

- P = power,
- E = electrical potential gradient perpendicular to plasma flow and magnetic field directions,
- J = current density component perpendicular to plasma flow and magnetic field directions,

A = cross-sectional area of generator,
x = unit length of generator.

5.2.2.6. Thermomagnetics. A driving magnetic field source has a shunt of magnetized material between its pole pieces. A wire coil is wrapped around either the pole pieces or the shunt, and then the shunt is subjected to rapid heating and cooling[8,9]. This thermal cycling causes the material to lose its magnetization as the temperature rises and regain it as it falls. As a result, a voltage is produced.

5.2.2.7. Thermally regenerative electrochemical systems (TRES). This is a general category of DEC[12], which produce electricity by converting low temperature heat in an electrochemical heat engine[33,34].

Three classes of TRES exist[34]. One is thermally regenerated, and another is regenerated by using electrolytic and thermal inputs. Regeneration can take place at temperatures higher or lower than that at which electricity is produced[33,35].

In the thermal regeneration TRES[34], a reaction takes place in an electrochemical cell at a given temperature, forming a product. This is accompanied by the production of electricity. This product is sent through a heat exchanger to a regenerator which is at a temperature either higher or lower than that of the reaction (depending upon the product). The product is thermally decomposed spontaneously, the constituents separated, and returned to the cell through a heat exchanger.

In the electrolytic and thermal regeneration TRES[36], a reaction product is formed at a given temperature in a cell, which is then sent through a heat exchanger to a regenerator. Electrolytic decomposition takes place at a higher or lower temperature (depending upon the product). This appears to be done by consuming a portion of the voltage produced from the reaction, using the remainder in the external circuit. The constituents return to the cell after passing through the exchanger.

A sub-category of the second TRES is mentioned in [12], and this is the thermogalvanic cell[37]. In this one, the electrolytic and thermal paths are together. At least two electrodes at different temperatures are in the electrolyte (either solid or liquid), which has a temperature gradient in it. Matter from one electrode moves to another due to reactions at the electrodes and the conduction of ions.

5.2.3. Liquid Fuel Atomizers.

5.2.3.1. Simplex nozzle. Fuel is injected into a swirl chamber, and moves out to the walls[13,14,15]. The combination of the radial and axial forces from this motion causes the fuel to emerge from the nozzle in a hollow cone. This nozzle has a set of internal passages constructed to prevent clogging.

5.2.3.2. Return-flow nozzle. Fuel is injected into a swirl chamber at a high pressure which causes the stream to move outwards towards the walls. A portion is atomized and the remainder is returned to the fuel supply[13,16,17,18]. Atomization is controlled by varying the fuel pressure, the fuel return rate, or possibly both.

5.2.3.3. Electric nozzle preheater. An atomizing nozzle is electrically heated to raise the fuel temperature prior to atomization[16,19].

5.2.3.4. Air atomization. Low-pressure fuel is mixed with high-pressure air prior to atomization[16,20].

5.2.3.5. Electrostatic atomization. An emitter charges the surface of the fuel flow, which is then deformed by the attraction from an oppositely-charged electrode[21]. Atomization occurs when the attractive force is greater than that exerted by the surface tension.

5.2.3.6. Fuel vaporizer. Liquid fuel is injected into a heated chamber, vaporized, and ejected through an orifice and a venturi, thus inducing combustion air[22].

5.2.3.7. Rotary burner (spinning disk). Fuel is metered onto a rapidly rotating distributer and the centrifugal force breaks the stream into a mist[23].

5.2.3.8. Catalytic burner. Vaporized fuel flows through a catalyst bed, which oxidizes it, releasing heat[24,25].

5.2.3.9. Ultrasonic atomization. Fuel is pumped onto a transducer which breaks the stream into a mist by means of ultrasonic waves generated by electrically-stimulated piezoelectric crystals[16,26].

5.2.3.10. Pulse burner. The pulse burner cycle starts by detonating a mixture of fuel and air[27,28]. The sudden increase in pressure expels the combustion products. The sudden expulsion creates a vacuum in the combustion chamber, drawing in more fuel and air for detonation. Also, some of the hot exhaust products are drawn in by the vacuum to provide re-ignition.

5.3. Technical Comparison

5.3.1. Direct Energy Converters.

5.3.1.1. General. The DEC's were judged on the following criteria:

- Commercialized technology, which represents an advanced state of development as not only has the technology in question been shown to work, but also operates reliably.

- Availability of working prototype, as commercial potential may exist with work being required to bring the technology to the market place.

- Adaptability to liquid fuel operation, as the DEC's must operate in the temperature range of a liquid fuel flame.

- Operating temperature below 1400°F, since DEC's and burners must be able to withstand long-term exposure to temperatures up to this value, allowing the system to be fabricated from alloys such as Inconel and Hastelloy.

- Solid state construction, because the heater system must function in any orientation, which would mean that one with a working fluid can be impaired in operation due to localized dry spots, and a required circulation system which would add to the heater size and weight.

- Silent operation, as field conditions dictate that the noise levels be low.

- Compactness, in order to meet the size and weight restrictions for the system.

- Time to readiness, since it is desired that useful power be produced within 15 minutes in order to reduce dependence upon external power.

The term "power density" is one that is frequently used in evaluating performance. This represents the amount of power that can be obtained per unit weight of the DEC without any accompanying support systems such as cooling. A high value indicates that a lighter generator is possible for a given power output.

Another term used in evaluating performance is "efficiency", and this represents the ratio of the amount of power produced for a given rate of heat input. In this application, the efficiency of a device is of lesser importance than the amount of heat delivered by the burner because heating is the primary requirement.

This is summarized in Table 5-1. Where possible, the values given were obtained from experimental or operational results. Those not available by this method were from theoretical projections.

Table 5-2 summarizes how each DEC conforms to the aforementioned requirements. This was compiled from published literature and by contacting appropriate investigators and manufacturers. For some DEC's, insufficient information was available to allow proper evaluation.

5.3.1.2. Thermoelectrics. This technology has been commercially available for approximately 20 years and has a demonstrated long-term reliability. This DEC has been used in liquid fuel-fired generators[2], has solid-state

Table 5-1. Direct Energy Converter Performance Comparison

Converter	Power Density (W/lb) *	Typical Device Efficiency (%)
Thermoelectrics	22.5	7.0
Thermionics	1000.0	13.0
Thermophotovoltaics	18.5	6.6-7.1
Sodium Heat Engine	113.4-226.8	19.0
Magnetohydrodynamics	N/A**	60.0
Thermomagnetics	0.02-68.0	1.2-12.8
Thermally Regenerative Electrochemical System (TRES)	N/A	N/A

* Low 0.0 - 15.0 W/lb
Medium 16.0 - 30.0 W/lb
High > 30.0 W/lb

** N/A = information not available

References:
Thermionics = 1
Thermophotovoltaics = 4
Sodium Heat Engine = 6,38
Magnetohydrodynamics = 1
Thermomagnetics = 10,11
TRES = 12

Table 5-2. Direct Energy Converter Technical Summary

	Converter*						
	TE	TI	TPV	SHE	MHD	TM	TRES
Commercialized Technology	Yes	No	No	No	No	No	No
Working Prototype	Yes	Yes	Yes	Yes	N/A**	No	Yes
Adaptable To Liquid Fuel	Yes	No	No	Yes	No	Yes	Yes
Operating Temperature <1400°F	Yes	No	No	Yes	No	Yes	Yes
Solid State	Yes	No	Yes	No	No	No	No
Silent Operation	Yes	Yes	Yes	Yes	N/A	Yes	Yes
Compact	Yes	Yes	Yes	Yes	No	No	No
Time To Readiness <15 Minutes	Yes	Yes	Yes	Yes	N/A	Yes	N/A

* TE = Thermoelectrics[1,2]
TI = Thermionics[1,3]
TPV = Thermophotovoltaics[1,4,5]
SHE = Sodium Heat Engine[6,7]
MHD = Magnetohydrodynamics[1,8,9]
TM = Thermomagnetics[10,11]
TRES = Thermally Regenerated Electrochemical System[12]

** N/A = Information Not Available

construction, and is silent in operation. These units are generally compact and produce useful power in under 15 minutes.

5.3.1.3. Thermionics. Experimental prototypes have been built, but this DEC technology is not known to be in commercial production. It may be adaptable to liquid fuel firing[3], but requires very high temperatures for efficient operating[1,3]. Many units use a conducting medium in the inter-electrode gap such as cesium or cesium-graphite vapour[3]. This means that the DEC requires a working fluid, including a heated reservoir. It produces little noise and gives useful power within 15 minutes.

5.3.1.4. Thermophotovoltaics. Working prototypes are known to exist, but this DEC does not appear to be commercially available. It may be adaptable to liquid fuel firing, but requires very high temperatures for efficient operation[1,4]. This means a specially designed burner system built from ceramic materials will be needed[4]. This DEC is noiseless and compact and produces useful power within 15 minutes.

5.3.1.5. Sodium heat engine. This DEC is being studied and working prototypes exist[6,7]. It appears to be adaptable to fuel-fired operation with temperatures below 1400°F possible. It produces little noise and produces useful power in less than 15 minutes. However, it requires molten sodium in order to operate and so a liquid metal circulation system is needed. This restricts the orientation of operation and adds to the overall size and weight. There is also some question as to the reliability and expected lifetime. Such devices may have to be cascaded in order to obtain the desired power levels[6].

5.3.1.6. Magnetohydrodynamics. Insufficient information was available to allow an adequate analysis of this DEC. No commercially available converters appear to exist[1,9]. The temperatures required for the liquid metal MHD units may make this DEC adaptable to liquid fuel-fired operation[9]. Those using plasmas require temperatures which would make the technology difficult to adapt[1,9]. The use of a liquid metal, an ionized plasma, and/or "seed" material implies the need for a working fluid, along with necessary support systems. Studies have shown that this DEC is being investigated for large-scale power station applications (at least 1 Megawatt in capacity) and is impractical for small portable operation.

5.3.1.7. Thermomagnetics. Theoretical research has been conducted and patents relating to this were filed in 1886 and 1887[10]. No working prototype is known to exist and so would be unavailable commercially. It appears to be suitable in other technical respects but may not be compact due to its required support systems, such as a superconducting magnet[11].

5.3.1.8. TRES[12]. Studies have indicated that this technology is still experimental, and is not known to be commercial. Insufficient information was on hand for full analysis, but it appears that a working prototype exists and that it may be adaptable to liquid fuel operation. They appear to be low in noise, but may not be compact. No definite time to readiness figure was available.

5.3.2. Liquid Fuel Atomizers.

5.3.2.1. General. The atomizers were judged on the following criteria.

- Commercialized technology, as this represents the viability of the technology in question, and indicates an advanced state of development and high system reliability.
- Variable fuel flow rates, as the atomizer must function effectively between 1.0 lb/hr (startup) and 5.0 lb/hr (steady-state operation).
- Fuel pressure, which should be minimized, eliminating high-pressure fittings and extending the fuel pump lifetime.
- Orientation, since the atomizer must function in any position.
- Multifuel capability, as the atomizer must handle fuels over the temperature ranges given in 5.1.1.
- Availability of working prototypes, as operating characteristics can be evaluated.
- No moving parts required for operation, as the reliability is increased and the system size and weight reduced.
- Minimum support systems required, such as pressurized air.
- Silent operation, because field conditions dictate that the noise levels be low.
- No external starting heat source required, since it is required that the heater start using the same fuel it is operating with and that atomization is initiated without any external heat.
- Compactness, in order to meet the system requirements for size and weight.

An analysis such as was done for the DEC's was conducted for the atomizers. The results are summarized in Table 5-3.

5.3.2.2. Simplex nozzle. This type of atomizer is commercially available and indications are that it is suited for this application in most respects[13,14,15]. It is operable in any position, and appears to have multifuel capability. It is silent in operation and is compact as it requires no moving parts or support systems. Its major disadvantage is that a high fuel pressure (recommended values often in excess of 15 psig) is needed for operation, and it may not be able to accommodate the required range of flow rates.

5.3.2.3. Return-flow nozzle. This type is commercially available and it is indicated that it is suited in most respects[13,16,17,18]. It appears

Table 5-3. Liquid Fuel Atomizer Technical Summary

	Simplex Atomizer	Return-Flow Nozzle	Electric Nozzle Preheater*	Air Atomiz.	Electrostatic Atomizer	Fuel Vaporizer	Rotary Burne.	Catalytic Burner	Ultrasonic Atomizer	Pulse Burner
Commercialized Technology	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
Flow Rate Of 1.0 - 5.0 lb/hr	No	Yes		Yes		Yes	No	Yes	Yes	Yes
Fuel Pressure <15 psig	No	No		Yes		Yes	Yes	Yes	Yes	Yes
Operable In Any Position	Yes	Yes		Yes		No	No	No	Yes	Yes
Multifuel Capability	Yes	Yes		Yes		No	Yes	No	Yes	Yes
Working Prototype Available	Yes	Yes		Yes		Yes	Yes	Yes	Yes	Yes
Moving Parts Required	No	No		No		No	Yes	No	No	No
Support Systems Required	No	Yes		Yes		Yes	Yes	Yes	Yes	Yes
Silent Operation	Yes	Yes		Yes		Yes	Yes	Yes	Yes	No
External Heat Source For Starting	No	No		No		Yes	No	Yes	No	Yes
Compact	Yes	No		No		No	No	No	Yes	No

* Not available as a combined nozzle-heater unit.

References:
Simplex Atomizer = 13,14,15
Return-Flow Nozzle = 13,16,17,18
Electric Nozzle Preheater = 16,19
Air Atomizer = 16,20
Electrostatic Atomizer = 21
Fuel Vaporizer = 22
Rotary Burner = 23
Catalytic Burner = 24,25
Ultrasonic Atomizer = 16,26
Pulse Burner = 27,28

that it can accommodate the fuel flow rate required, has multifuel capability, is operable in any position and requires no moving parts. It requires, though, a high fuel pressure (recommended values often in excess of 15 psig) and a fuel return line.

5.3.2.4. Electric nozzle preheater. In-line heaters are commercially available and one type shows potential for this application[16,19]. Indications are that commercially available atomizer nozzles (such as the return-flow type[13,16,17,18]) can be fitted to them, either directly (if the nozzle and heater threads match) or with minor modifications. These heaters may possibly be operated from a 28 VDC power supply, but do not appear to have a low power consumption (10 W or less). It is possible that these could be used to reduce the fuel viscosity during low-temperature starts.

5.3.2.5. Air atomization. This type of atomizer is commercially available and meets most of the technical requirements[16,20]. It can handle the required variation in fuel flow and can operate in any position. It has multifuel capability and requires no moving parts. It is silent in operation and requires no external heat to initiate atomization. However, a pressurized air supply is required to operate it.

5.3.2.6. Electrostatic atomizer. Since studies indicate that no active research is being conducted on the electrostatic fuel atomizer and there does not appear to be any commercially available units, it is not considered suitable for this application[21].

5.3.2.7. Fuel vaporizer. Fuel vaporizers are commercially available[22]. They operate effectively over a range of flow rates and require less than 15 psig fuel pressure. They are limited in operating orientations and do not appear to have multifuel capability. No moving parts are required but an external heat source is needed to start them. Consequently, they are not compact and are not considered suitable for this application.

5.3.2.8. Rotary burner. Rotary burners are commercially available but studies indicate that they are limited in their applicability[23]. They have fixed fuel flow rates and are restricted in their operating orientation, according to one manufacturer. The fuel pressure is less than 15 psig and they can handle a variety of fuels, plus being silent in operation. Their major drawback is that a drive motor for the rotary element is required as well as a specially designed fuel pump.

5.3.2.9. Catalytic burner. Catalytic burners are commercially available for heating applications but studies indicate that none exist for diesel fuels[24,25]. They can handle a variety of fuel flows and have fuel pressures less than 15 psig. However, they may not have multifuel capability, depending upon the catalyst used[25]. One advantage is that no moving parts are required but the fuel must be vaporized prior to ignition. This means a vaporizer is needed if they are to be used with liquid fuels, which would restrict burner orientations and increase size.

5.3.2.10. Ultrasonic atomizer. This type of atomizer is commercially available and can handle a range of fuel flows[16,26]. Fuel pressures below 15 psig are possible and the atomizer is operable in any position. It has multifuel capability and has no moving parts. It is silent and compact, with the major drawback being that a high frequency electronic oscillator is needed.

5.3.2.11. Pulse burner. This is commercially available technology and is used in a number of applications such as residential heating[21,22]. The pulse burner can handle a variable fuel flow rate and can operate with fuel pressures below 15 psig. The pulse burner is extremely noisy and is generally not compact. This technology is best suited for gasoline operation and is not easily adapted to diesel fuel combustion.

5.4. Economic Comparison

5.4.1. Direct Energy Converters. Several investigators and manufacturers involved with DEC's were contacted regarding the fabrication costs and estimated lifetimes for the various converters. This is presented in Table 5-4. The cost analysis is based on existing manufacturing, and does not necessarily reflect mass production. This is the only unbiased way to make comparisons between DEC's with the least amount of extrapolation and conjecture.

As far as possible, prices were obtained in terms of U.S. funds. When this was not the case, an exchange rate of $1.37 Canadian per $1.00 U.S. (as of May 31, 1986) was used. Inflation was accounted for at a rate of 5.0 percent compounding.

It should be noted that no information regarding the economics of the magnetohydrodynamics[1,8,9] and TRES[12] DEC's was available.

Of the remaining DEC's, thermophotovoltaics[1,4,5] and thermomagnetics[10,11] have the lowest costs. The former figure is for the DEC photocells alone and may not include such things as engineering of the photocell array, tooling and manufacturing labour. Due to the high operating temperatures required, a burner and emitter made from special ceramic materials would be required for a complete generator. It was learned through discussions with an investigator that this could bring the overall price to approximately that of thermoelectrics. Also, a lifetime figure for such a DEC does not appear to be available, as it did not appear that a complete generator has been built and tested.

The thermomagnetic cost is based on a value for a 10 MW system[11], and appears to be for materials and labour only. However, since a working prototype would have to be built, there would be additional costs for development. The price shown is based on 1984 dollars extrapolated to 1986 funds at a rate of 5.0 percent.

Thermionics[1,3] and the sodium heat engine[6,7] have both the highest costs and the shortest lifetimes, these values being obtained from

Table 5-4. Direct Energy Converter Economic Summary (Nonproduction)

Converter	Fabrication Cost ($US/Watt)	Estimated Lifetime (Hours)
Thermoelectrics	15.00	175,200
Thermionics	683.00	12,500
Thermophotovoltaics	0.26	N/A*
Sodium Heat Engine	<1,025.00	10,000
Magnetohydrodynamics	N/A	N/A
Thermomagnetics	1.77	N/A
TRES**	N/A	N/A

* N/A = Information Not Available
** Thermally Regenerated Electrochemical System

References: Thermionics = 1
Thermophotovoltaics = 4
Sodium Heat Engine = 6,38
Magnetohydrodynamics = 1
Thermomagnetics = 10,1[illegible]
TRES = 12

discussions with investigators working with these devices. The thermionic[1,3] cost is for the development of a 60 W unit, but it is believed that in production runs of about a million units, this could be reduced to $800 per kW. The sodium heat engine[6,7] cost is an approximate estimate for the fabrication of experimental units, as production figures did not appear to be available. This may be significantly reduced with further work.

The thermoelectric cost is for the labour and materials to construct a new prototype, with no mass production. This is based upon a military grade radial design with a higher power density than previous units of this type. The figure in Table 5-4 does not include development costs for such things as engineering. It should be noted that commercial grade flat plate thermoelectric DEC's can be built (labour and materials only) for $8.03/watt (1986 dollars and $1.37 Canadian/$1.00 American). See par. 5.9.1.4. for details. The price per Watt of a thermoelectric generator includes the device to house the thermoelectric material. When only the cost of the thermoelectric material segments is analysed, the price (including labour and material) is approximately $0.43/Watt. However, the thermoelectric material requires the additional $7.60/Watt worth of device to be functional.

5.4.2. Liquid Fuel Atomizers. A number of manufacturers and investigators of atomizers were contacted regarding the costs of fabrication or purchase of individual units as well as the estimated lifetimes. Findings were compiled and appear in Table 5-5.

Studies have indicated that electrostatic atomizers[21] for diesel fuels are not known to exist on a commercial basis and that they are not a topic of active research.

Studies have also shown that electric nozzle preheaters[16,19] are not so much a new method of atomization, but a means of improving the performance of an existing nozzle[16], and so, cannot be considered any further.

The pulse burner[27,28] has the highest cost and the longest lifetime. The cost is an assumed estimate to build an experimental unit using diesel fuel similar to one described in [28]. The lifetime is an estimate derived from that for a commercially available natural gas fueled residential heating unit. An external starting system such as pressurized air and starting heat[28] would be required. It must be noted that this is a combustion chamber as well as an atomizer.

The catalytic burner[24,25] has a shorter life than the pulse burner[27,28], but a comparable cost. The former figure is an approximate estimate for a commercial grade heating unit, with the latter for two 45,000 BTU/hr heaters. For effective operation with liquid fuels, a vaporizer would be required. No catalytic burners appear to exist for diesel fuel operation, however they are available for kerosene and lighter fuels.

The ultrasonic atomizer[16,26] lifetime is based upon values obtained for units already in place in other applications. It has a lower cost than the

Table 5-5. Liquid Fuel Atomizer Economic Summary (Nonproduction)

Atomizer	Estimated Cost** (US$)	Estimated Lifetime (Hours)	Required Support System
Simplex Atomizer	<3	4,000	None
Return-Flow Nozzle	101	8,760	Fuel return line
Electric Nozzle Preheater	Not known to be available as integrated heater-nozzle unit		
Air Atomizer	189	17,520	Air supply
Electrostatic	Not known to be actively researched		
Fuel Vaporizer	225	2,160	External starting heat source
Rotary Burner	116	3,400	Driver motor, fuel pump
Catalytic Burner	2993	26,280	Fuel vaporizer
Ultrasonic	450	17,520	Electronic driver
Pulse Burner	3000+	70,000	External starting heat and air source

* N/A = Information Not Available
** Exchange rate of $1.37 Canadian/$1.00 U.S. assumed
\+ Experimental test unit burning diesel fuel only

References:

Simplex Atomizer = 13,14,15	Fuel Vaporizer = 22
Return-Flow Nozzle = 13,16,17,18	Rotary Burner = 23,
Electric Nozzle Preheater = 16,19	Catalytic Burner = 24,25
Air Atomizer = 16,20	Ultrasonic Atomizer = 16,26
Electrostatic Atomizer = 21	Pulse Burner = 27,28

pulse burner[27,28] and catalytic burner[24,25]. An electronic driver is required but this is included in the price and in the lifetime figure.

Of the remaining atomizers, the air atomizer[16,20] has the second-highest single unit cost (as given by a supplier) but also the longest life, which is based on replacement times suggested by the manufacturer. As it requires a pressurized air supply, the overall atomization system cost will increase.

The rotary burner[23] has a low single unit cost but a shorter lifetime, according to one manufacturer. A driver motor is required for the atomizer, but its cost and life are included in the figures given. The lifetime is a minimum required value, though values as low as 600-800 hours have been mentioned. A fuel pump specifically built for this type of unit would be needed and would be about $70.

The fuel vaporizer[22] price is higher than that for the air atomizer[16,20], which is for labour and materials only. Its lifetime is based on actual field performance. Also, external starting heat is required, which would increase the overall price.

Of the pressure nozzles, the simplex atomizer[13,14,15] and return-flow nozzle[13,16,17,18] have the lowest costs, but different lifetimes (based on a manufacturer's recommendation and assumed intermittent operation for the former), with the former being the least expensive of all the atomizers. The latter, however, requires external support, which would add to the overall cost.

5.5. Final Selection

5.5.1. Direct Energy Converters.

Due to incomplete information, the magnetohydrodynamics[1,8,9] and thermally regenerative electrochemical system[8] DEC's can be eliminated as proper evaluation could not be made. This lack of information indicates that the technology is insufficiently developed and may not be applicable for the heating concept being studied.

The lack of a known working prototype for the thermomagnetic generator[10,11] makes judgement of performance difficult as it is not known that this technology can work. Also, this means that pre-production development costs would increase as a unit must be demonstrated to operate reliably.

The major disadvantage of the sodium heat engine[6,7,38] is the requirement for liquid sodium and a circulation pump. This adds weight and volume plus restricting the orientation of operation, making it unsuitable for use in the portable heater. It is also the most expensive DEC to build, based on available figures and the required development in order to bring the technology to a commercial level. It is also known that there are still fundamental difficulties with the porous electrodes.

Thermionics[1,3] and thermophotovoltaics[1,4,5] operate in about the same temperature range which makes a burner system built from ceramic materials necessary. Although the thermionic DEC[1,3] has a demonstrated lifetime, the use of a medium in the inter-electrode gap (such as the cesium or cesium-graphite vapour mentioned in [3]) may restrict the orientation of operation. It would also add weight and volume due to the addition of a reservoir and associated components. It is considerably higher in cost than most of the other DEC's.

In comparison, the thermophotovoltaic DEC[1,4,5] is compact and less expensive. However, in order to produce power, a specially-built burner and emitter is required, the cost of which was estimated as follows. Based on dimensions in [4], (for a 1,000 W generator) the radiator size was assumed to be a thin-walled cylinder with an end cap 25 cm high, 10 cm outer diameter, and 0.1 cm wall thickness. Assuming Er_2O_3 as the material[4] and using cost and density figures provided by a chemical supplier, the price for the radiator was determined. It was also assumed that the remainder of the burner would cost the same amount. This does not include such things as labour, engineering, and assembly. The estimated price was about $6,385.00.

Two investigators in thermophotovoltaics[1,4,5] were contacted concerning these costs. No consistent figure was obtained since this would depend upon the design and materials used. Fabrication details were unavailable in one instance as access to the information was restricted.

Of all the DEC's, thermoelectrics have the best conformity to the technical requirements given in 5.3.1.1. From Table 5-4 they would be the most cost-effective, having the longest lifetime.

By process of elimination, based upon available information, the recommended DEC would be the thermoelectric converter.

5.5.2. Liquid Fuel Atomizers.

Since the electrostatic atomizer[21] does not appear to be a subject of active research and is probably not commercialized, it can be eliminated as little information was available to allow an adequate analysis.

The electric nozzle preheater[16,19] is not an atomizer as such, and so can be discounted as a candidate.

Since a variable flow rate capability is required, the rotary burner[23] may not be suitable as it does not appear to have it, based upon discussions with one manufacturer. A drive motor and a specially-designed pump are also required for the atomizer to function.

The requirement for the heater to be operable in any position would eliminate the fuel vaporizer[22] as it would not be suitable for portable operation. It also has the shortest known lifetime of all the atomizers, which reduces its cost effectiveness. Also it requires external heat to begin operating.

This would also eliminate the catalytic burner[24,25] as it would require some form of fuel vaporization in order to operate from liquid fuels. It also has the second-highest cost of all the atomizers, requires external starting heat, and probably would not be compact.

Silent operation is a system requirement and the pulse burner[27,28] examined would not be suitable. It also requires starting heat and air, resulting in added size and weight. In addition, it has the highest cost of all the atomizer systems.

The remaining atomizers are the simplex atomizer[13,14,15], the return-flow nozzle[13,16,17,18], the air atomizer[16,20], and the ultrasonic atomizer[16,26]. All of these fulfill most of the technical requirements in par. 5.3.1.2. and have long lifetimes.

The air atomizer[16,20] requires an external air supply in order to function for which an air compressor is needed. This would increase the required power output of the DEC to be used and therefore the size and volume of the heater would rise. Also, the cost of the overall atomization system would be raised with the addition of the compressor.

Of the two remaining pressure atomizers, the return-flow nozzle[13,16,17,18] is the more expensive (according to a supplier) and it also requires a means of returning fuel to the supply, which increases the overall cost. In contrast the simplex nozzle[13,14,15] is considerably lower in price and requires no support system. But it does not appear to have the desired fuel flow rate variation, which the other one has.

The ultrasonic atomizer[16,26] may have a high initial cost for a military grade prototype but this can be reduced when mass-produced. It has a long lifetime and can operate at a low fuel pressure, which, according to the information obtained, neither the return-flow nozzle[13,16,17,18] nor the simplex nozzle[13,14,15] can do. This lower pressure may have an added overall cost saving as the wear on the fuel delivery system would be reduced, extending its lifetime, plus possibly reducing its power consumption.

By process of elimination, based upon information available, the ultrasonic atomizer[16,26] would be preferred for the combustion system, with the return-flow nozzle[13,16,17,18] being the alternate choice.

5.6. Technical Consultations

5.6.1. General. A number of direct energy converters and liquid fuel atomizers were evaluated from available technical and economic information. Several individuals who are involved with them either as manufacturers, suppliers, investigators, or end users (either direct or as original equipment manufacturers - OEM's) were contacted to determine, if possible, the performance and shortcomings of the thermoelectric DEC[1,2], the ultrasonic atomizer[16,26], and the return-flow nozzle[13,16,17,18].

5.6.2 Thermoelectrics.

5.6.2.1. Manufacturers. A number of firms are involved in the manufacture of thermoelectric DEC's[1,2], both in military and commercial grades.

Commercial fuel-fired generators using this DEC are generally trouble-free, but problems have been known to arise. Many of the difficulties have been due to support system failure, often due to poor fuel quality. This can result in problems such as the fuel regulator freezing in low temperatures.

Usually the cause of DEC failure is excess heat, which damages the walls of the combustion chamber and the thermoelectric assembly. This, though, is not easily done and is not a common occurrence.

The thermoelectric DEC[1,2] was chosen to be the best suited for this application, both technically and economically. Furthermore, it is possible to reduce the cost of production below the value given in Table 5-4 and research is being conducted for that purpose. For example, one project of this nature has been undertaken by Global Thermoelectric.

5.6.2.2. End users and investigators. This DEC has been tested by the Canadian Department of National Defence (DND) specifically for cold weather starting of vehicle engines. The results of these tests appear in [39]. The vehicles used for the test were a Lynx (referred to in the report as "D418")[40], and an MLVW ("D419")[40]. This was compared with an auxiliary diesel engine used on a Lynx and a 5-ton truck ("D420")[41]. The purpose of this test was to assess the effectiveness of engine heating and engine heater performance.

A number of results indicated that the thermoelectric DEC[1,2] was suitable. On the D419, at temperatures down to -40°F (-40°C), the vehicle engine could be started in less than ten seconds[42]. This was after it was preheated about 10 to 30 minutes[43]. Ambient temperatures were from -4°F (-20°C) to -40°F (-40°C). For temperatures below -40°F (-40°C), engine starting was achieved within 30 seconds on the D149 test vehicle[44].

At extremely cold temperatures the thermoelectric engine heater being tested was statistically better in providing main engine starts[45]. The report concluded that to take full advantage of the thermoelectric engine heater future designs should be packaged to provide better accessibility[46].

The thermoelectric engine heater tested by the Canadian DND is the first known application of thermoelectrics for vehicle engine heating. Many technical difficulties were encountered and resolved to provide a heater that would provide engine coolant heating at -40°F (-40°C), using diesel fuel, and be self-sustaining. Through discussions with an official from DND, it was learned that the heaters were breadboard units, possibly requiring about two additional design stages prior to production.

Commercial users of natural gas-fired thermoelectric[1,2] generators have experienced few difficulties with the DEC's. One is corrosion of the combustion chambers due to fuel contaminated with such gases as hydrogen sulphide, which attacks the alloys used (usually Inconel and Hastelloy). The overheating mentioned in Par. 5.6.2.1. has usually been attributed to operator error. In a number of cases, the generators have operated unattended for more than 5 years. Physical damage other than overheating has been known to occur, but is very rare and usually operator-related.

5.6.2.3. Comments and suggestions. The general reaction of users of commercial thermoelectric[1,2] generators was satisfaction. This was largely due to the DEC reliability and durability plus the fact that the generators can be operated unattended for long periods of time. One immediate benefit was a reduction in operating and maintenance costs.

When the DND official was contacted concerning the tests described in [39], the opinion was expressed that the method of heating vehicle engines using a DEC was the only suitable approach. Plans are currently underway to continue development of this concept.

5.6.3. Ultrasonic Atomizer.

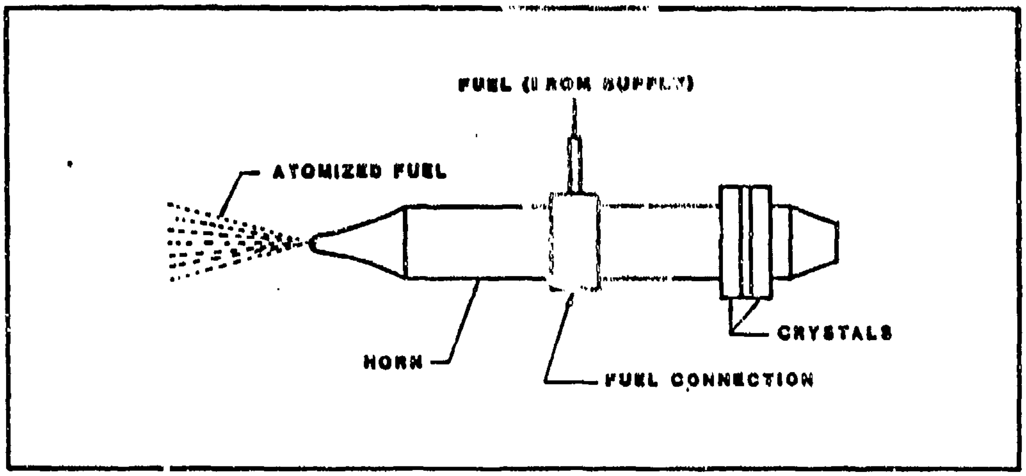
5.6.3.1. Manufacturers. Ultrasonic atomizers[16,26] using piezoelectric crystals are manufactured by several firms and are used in a number of applications. Two types are known to exist — ones using an acoustic horn for atomization and those using a vibrating disc[47]. Figure 5-1 depicts them.

There are difficulties associated with them. Quality control is a major concern as consistency in the final product appears difficult to achieve. The system impedance varies, often resulting in a higher current being required, ultimately affecting the performance.

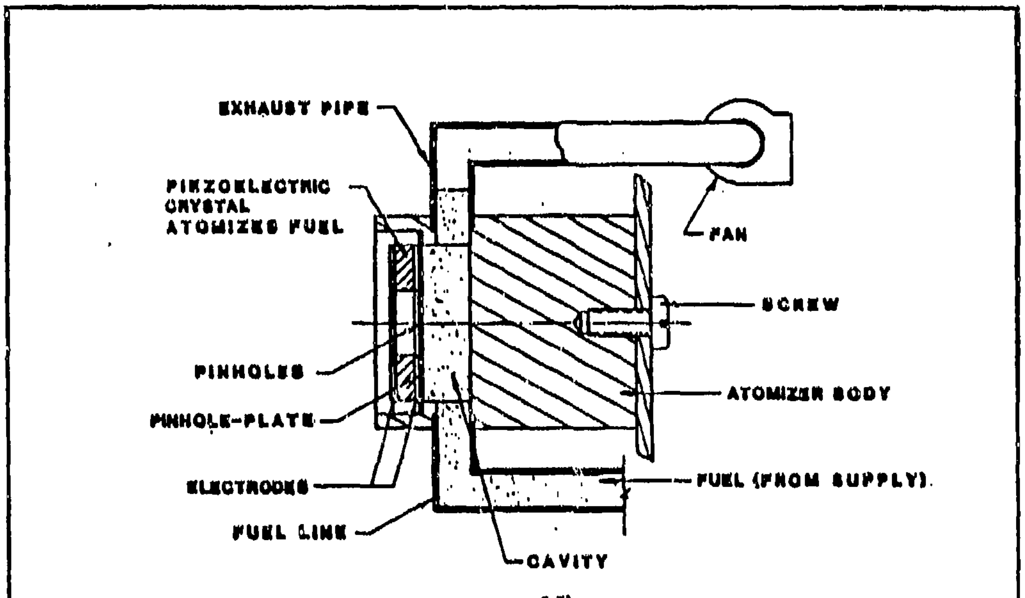
The crystal is another problem area. A suitable means of fastening it in place has yet to be found. Crystals have been known to crack when hot, due to their brittleness, and their performance characteristics change with temperature.

The atomizer performance is dependent upon the frequency of oscillation and is designed ("tuned") to resonate at a given value. This can be affected by changes in temperature, largely due to the crystal characteristics being altered. Radiant heat from the burner flame warms the atomizer tip, which is then conducted along the horn to the crystal. Maintaining a cool operating temperature below 212°F is essential in providing long life and steady atomization. The horn design inherently operates the crystal at lower temperatures than the vibrating disc[47] style.

Higher resonant frequency designs are possible, but the atomizer horn would have to be shorter (due to the shorter wavelength), which could result in higher crystal temperatures. Also, a shorter horn would restrict the access of the fuel line connection.



HORN



NOTE: DEPICTION BASED ON [47]

VIBRATING DISC

TACOM 7000-1-3

FIGURE 5-1. TYPICAL ULTRASONIC ATOMIZERS

As there are a number of uncertainties about the atomizer behaviour, evaluation of a combustion system failure can be difficult. Malfunctions may not necessarily be due to the atomizer, but could be attributed to the burner itself.

Operation of the atomizer with the tip pointing up may give rise to fuel dripping down on it. This may be solved if the fuel stream is taken away from the tip by a suitable burner design, including having sufficient incoming combustion air and efficient combustion.

However, in spite of these difficulties, the ultrasonic atomizer[16,26] is an effective system. It has the desired atomization performance for the low fuel flow rates that would be required, and appears to be well-suited for operating in the required temperature range. The mist produced is high quality, allowing efficient combustion.

Presently, there is an ultrasonic atomizer[16,26], designed by Global Thermoelectric, that has proved to be very successful in providing both excellent ignition and good smokeless combustion. This atomizer is currently on life test and has accumulated over 1,200 operating hours, with no indication of deterioration. It has been tested in temperatures from -40°F (-40°C) to +122°F (+50°C) with no deviation in performance. This was for both ignition and steady-state combustion. Figure 5-2 shows a typical unit atomizing water into a very fine mist.

5.6.3.2. End users and investigators. There do not appear to be a large number of end users and investigators of ultrasonic atomizer[16,26] specifically involved in the areas of low temperature combustion and vehicle engine heating. Tests using this type of atomizer are described in [39]. However, a number of atomizers are being used in a commercial application to power thermoelectric generators.

Some of the atomizers in these generators have failed. The exact cause is unclear, but overheating of the horn during operation, subsequently damaging the crystals, is believed to have been the reason. Another one occurs after shutdown, in which radiant heat from the combustion chamber is conducted along the horn, and damaging the crystals.

Driver circuits have failed, and it is believed to have been because the atomizer itself stopped oscillating, most likely due to crystal damage. This resulted in higher power consumption which damaged some of the components as no provision for circuit shutdown was made.

Over 50 of the generators are in place and have been operating for more than 3 years. No sudden failures of the atomizers have been reported to have occurred. It should be noted, though, that the ambient operating temperature is well above freezing.

An atomizer of the same design had been used on the thermoelectric heater described in [39]. An official from DND was contacted and it was mentioned that the atomizer had malfunctioned, though it was believed to

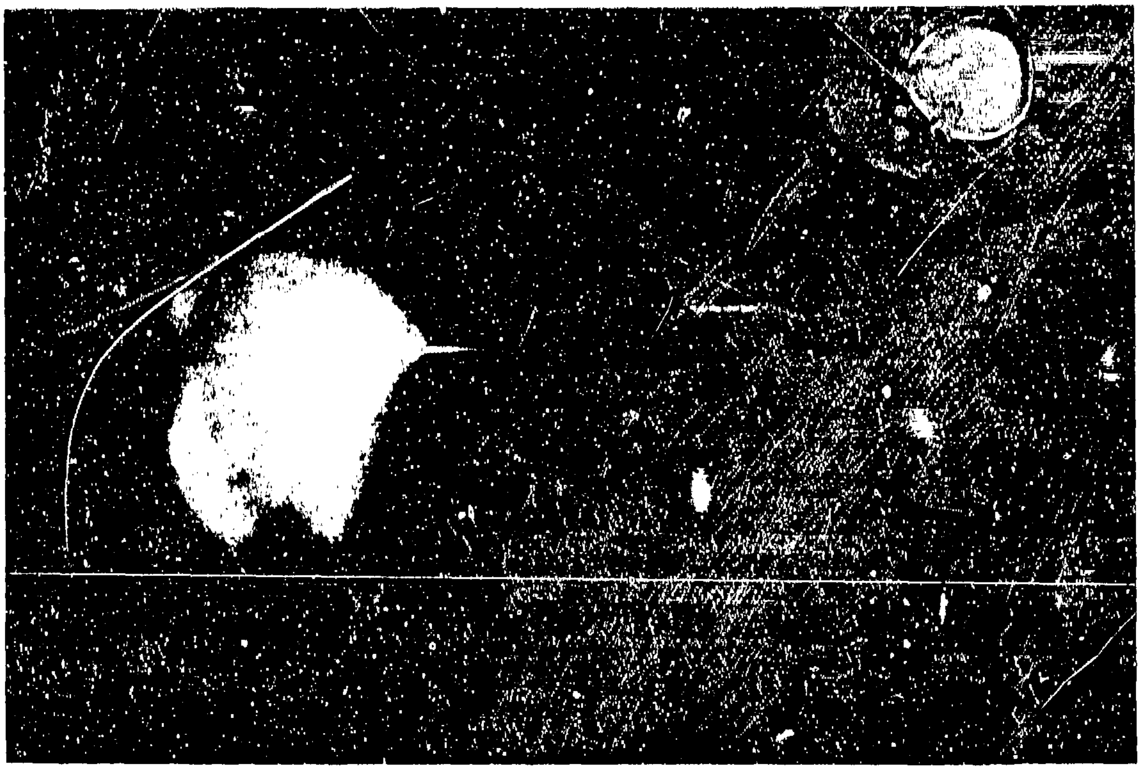


Figure 5-2. Ultrasonic Atomizer Operation (Horizontal Orientation)

have been due to electronic failure. However, this point is unclear, as an exact diagnosis as to whether it was due to the circuitry or waxing of the fuel could not be performed[46].

It should be noted that according to DND, the heater was a breadboard unit. This was the first time that the atomizer was known to have been operated at low temperatures.

Combustion is not the only end use for ultrasonic atomizers. Other applications are humidity control, such as in meat coolers. These atomize water between 32°F (0°C) and 39°F (4°C) to produce a fine mist which diffuses through the air. This mist is opaque and serves to keep the meat moist. This atomizer is operated by a crystal at a higher frequency, forming smaller droplets as larger ones would precipitate and cause the windows to fog. Household humidifiers using this type of atomizer are also available and are very popular due to their low cost, small size and silent operation.

5.6.3.3. Comments and suggestions. The general assessment of the ultrasonic atomizer[16,26] was that it was the best-suited method for atomizing liquid fuel, despite the problems associated with its manufacture. Those units that operated did so satisfactorily, giving a very fine mist and experiencing little clogging, unlike pressure nozzles such as the return-flow[13,16,17,18].

It was for that very reason that it was preferred over the pressure nozzles when DND awarded a development contract for a small portable generator. Other atomizers have difficulty in producing a satisfactory mist at the low fuel flow rates and pressures, while the ultrasonic atomizer[16,26] can function effectively at pressures near zero psig using any fuel type.

This technology is used in a wide variety of applications in fields other than combustion, but few of them, if any, would approach the conditions associated with cold-temperature vehicle engine heating. It is this which causes the difficulties being experienced with all types of atomizers.

It should also be noted that when assessing the suitability of an ultrasonic atomizer[16,26], one should remember that an extremely high potential for it exists. Improvements are expected and this atomizer represents state-of-the-art technology. Major breakthroughs in pressure nozzles are not foreseen, and are not generally used in extreme cold.

5.6.4. Return-Flow Nozzle.

5.6.4.1. Manufacturers and distributors. A major manufacturer of spray nozzles had been contacted with regards to the best atomizer for this application. The air atomizer[16,20] was suggested by them, with the return-flow nozzle[13,16,17,18] as the second choice.

These were recommended because nozzles of these designs are often used in heating applications, particularly in residential and industrial settings. Their major technical advantage is that the required turndown ratio for this application could possibly be accommodated. However, the lower flow rates may pose a problem as the fuel may not be atomized to the high quality essential for ignition.

Since a return-flow nozzle[13,16,17,18] was selected in par. 5.5.1., the discussions concentrate on this atomizer.

No clear indication was given on how the atomization could be controlled, but the manufacturer's literature shows that the fuel line pressure can be kept constant while the bypass flow rate is varied. Also, it is not clear if a stock atomizer can be used in the required temperature range, as its effectiveness may be restricted.

Due to the uncertainties regarding the applicability of a commercially-available stock nozzle, the manufacturer had suggested that possibly a custom-built unit of this variety may be used.

A representative of the manufacturer was contacted concerning the return-flow nozzle[13,16,17,18]. Among the comments that were made was that carbon build-up on the atomizer is possible, but this can occur when the fuel delivery system is shut off and the pressure gradually lowered. The degree of atomization is reduced and the combustion incomplete, resulting in the formation of soot. This would be less likely to take place when the fuel flow is quickly shut off by, for example, a solenoid valve.

5.6.4.2. End users and investigators. A number of end users of these nozzles were contacted with respect to such things as the application, fuel atomized, flow rate and pressure and operating difficulties. They were all used for heating, though none were for vehicles in cold climates.

In most cases, they were used for process heating (such as steam boilers) though one was for an experimental retrofit on an oil furnace. All burners used #2 fuel, with other fuels (diesel, and what was mentioned as "arctic") being used on occasion.

The flow rates were generally higher than what is required for this application, ranging from an estimated 1 GPH (though this value was not known for certain) to about 35 GPH. Fuel pressures varied as well with values from 100 psig to 400-600 psig being given. No consistent figures were available. One end user mentioned that better atomization was possible with higher pressures.

In most cases, the atomizers were horizontally mounted, but one was in a vertical orientation. Two end users were equipment manufacturers and expressed that vertical mounting of these nozzles was possible, though difficulties may be encountered. One was that there may be problems associated with fuel dripping and another was carbon build-up. No indication was given that these were insoluble.

No clear indication as to the atomizer lifetime was given, as in most cases, proper records were not kept. However, in some instances, operating times of 6 months had been mentioned (presumably for continuous service). One user indicated that nozzle erosion was possible, depending upon the fuel volume and lubricity. Another mentioned that fuel cleanliness may be a factor worth considering.

A number of methods for controlling the performance of the nozzle were used. In most cases, the bypass rate (that is, the rate at which fuel is returned to the supply) was adjusted. This may have been done together with an adjustment in the air flow to the burner. Most users kept the fuel line pressure constant.

No indication was given that the nozzles were used in low temperature environments. One equipment manufacturer suggested that the fuel be preheated (especially at low flow rates) or that excess combustion air be used. It was also suggested that the burner be designed so that the air can be preheated.

The general reaction was that the nozzles performed satisfactorily with no major problems being encountered. Any difficulties that were experienced were due to factors not directly related to the nozzle itself.

5.6.4.3. Comments and suggestions. General satisfaction with the performance of the return-flow nozzles[13,16,17,18] was expressed by the end users. No major difficulties were reported, but the atomizers were not used in conditions similar to those for this application.

The manufacturer contacted indicated problems may arise, particularly at low fuel flow rates, but there did not appear to be any data available on the nozzle performance at those values over the required temperature range. One end user suggested as a possible solution, that several nozzles, such as the simplex[13,14,15] nozzles, be used. Each would cover a given flow range, with the combustion system switching between them when the applicable amount of fuel was delivered.

5.7. Heater Design Considerations

5.7.1. General. This section contains the technical and manprint requirements for the heater, as well as what would be required in order to complete the design.

5.7.1.1. Solicitation requirements. Table 5-6 summarizes the technical requirements outlined in the original solicitation[48] number DAAE07-85-R-R036. The heater design must make provision for each of them.

5.7.2. Mechanical.

5.7.2.1. Burner fuel system.

- The burner must burn the required fuels given in Technical Requirements paragraph C.3.2.5 over the temperature range of -65°F to +70°F (as per Technical Requirements paragraph C.3.2.1).

Table 5-6. Heater Technical Requirements (Solicitation)

Technical Requirements Paragraph		Heater Concept Addresses		
		Personnel	Coolant	Portable
C.3.1	Major Sub-componentry	All	All	All
C.3.2	Thermal Output (BTU/hr)	0-60,000	0-30,000	0-40,000
C.3.2.1	Operating Range	X	X	X
C.3.2.2	Delivered Output	190 cfm	80-100 gph	100-200 cfm
C.3.2.3	Self-sustained & Start with ≤ 20 Amps	X	X	X
C.3.2.4	Mean Time Between Failures (hrs)	1000	1000	1000
C.3.2.5	Multifuel, if Fuel Fired	X	X	X
C.3.2.6	Modular Design	X	X	X
C.3.2.7	Start Within 4 Min.	X	X	X
C.3.2.8	Maximum Fuel Consumption	X	X	X
C.3.2.9	Acoustic Noise & Electromagnetic Interference	X	X	X
C.3.2.10	Withstand Shock & Vibration	X	X	X
C.3.2.11	Minimize Special Tools/ Equipment	X	X	X
C.3.2.12	Weight & Size	X	X	X
C.3.2.13	Safety Shutdown	X	X	X
C.3.2.14	Chemical Resistant	X	x	X
C.3.2.15	Safety	X	X	X
C.3.2.16	Operating Position	X	X	X
C.3.2.17	Interchangeability	X	As much as possible	
C.3.2.18	Nuclear, Biological, and Chemical Environment Operation	X	-	-
C.3.2.19	Compatible to Liquid Heat Exchangers	X	X	If possible
C.3.2.20	Portable Operation	-	-	X
C.3.2.21	Hand Held Operation	-	-	X
C.3.2.22	Simple To Operate & Maintain	-	X	X

X = required
\- = not applicable

Based on [48]

- The fuel atomizer must function without clogging over the same temperature range.

- The fuel atomizer must function effectively at a fuel flow of 5.0 lb/hr (see Technical Requirements paragraph C.3.2.8) at temperatures from -65°F to +70°F.

- The fuel pump must be capable of delivering the following:

DF-2, F-54	0°F - +70°F
DF-1	-25°F - 0°F
DF-A	-65°F - -25°F
JP4, JP5	-65°F - +70°F
MOGAS	-65°F - +70°F
Gasoline (Automotive, Leaded and Unleaded)	-65°F - +70°F

in accordance with Technical Requirements paragraph C.3.2.5.

- The fuel delivery system output pressure will be between 3 to 15 psig, according to Technical Requirements paragraph C.3.2.8.

- The fuel delivery system must be operable in any position (according to Technical Requirements paragraph C.3.2.16).

- The fuel is to be delivered by an electrically-operated fuel pump to the personnel or coolant heaters and from a pressurized fuel tank for the portable heater.

- The heater must start within 4 minutes (in keeping with Technical Requirements paragraph C.3.2.7), using the fuels mentioned in Technical Requirements paragraph C.3.2.5 over the temperatures given in Technical Requirements paragraph C.3.2.1.

5.7.2.2. Combustion air.

- The combustion blower must deliver sufficient air for combustion over the temperature range of -65°F to +70°F (see Technical Requirements paragraph C.3.2.1) and fuel flow of 5.0 lb/hr (Technical Requirements paragraph C.3.2.8).

- The combustion blower shall have sufficient static pressure available to operate each of 3 heaters, in accordance with Technical Requirements paragraph C.3.2.2.

- The combustion blower must be adjustable to accommodate changes in ambient air temperature and fuel flow.

- The blower must be operable in any position, to meet with Technical Requirements paragraph C.3.2.16.

- The combustion blower motor electromagnetic interference (EMI) limit must comply with MIL-STD-461B and MIL-STD-462, according to Technical Requirements paragraph C.3.2.9.

- The combustion air supply must be independent of that for ventilation, as per Technical Requirements paragraph C.3.2.18 (dual air system).

5.7.2.3. Ignition system.

- The ignition system must deliver sufficient energy to initiate combustion over the temperature range from -65°F to +70°F (see Technical Requirements paragraph C.3.2.1).

- The ignition system must operate reliably and be effective with all fuel types over the full ambient temperature range -65°F to +70°F.

- The ignition system must have EMI shielding to meet the requirements of MIL-STD-461B and MIL-STD-462, as per Technical Requirements paragraph C.3.2.9.

- The ignition system lead lengths must be minimized.

- The ignition system must be easily accessible for maintenance in compliance with Technical Requirements paragraphs C.3.2.11 and C.3.2.22.

5.7.2.4. Thermoelectric converter cooling.

- Must be air cooled.

- The distance between the circulating fan and the thermoelectric converter (TEC) must be minimized.

- The diameter of the fan should be equal to the diameter of the TEC cooling fin base to give the least resistive flow path for the circulating air.

- The cooling fin design must maximize the number of leading edges to enhance heat transfer without significant increases in static pressure.

- The TEC cooling fins must be fabricated from aluminium.

- The TEC length-to-diameter ratio must be optimum for cooling, power generation, and available space.

- The number of obstructions between the cooling fan and the TEC, such as pinch-off tubes, power headers, and shunt regulator must be minimized.

5.7.2.5. Exhaust delivery.

- Sufficient exhaust static pressure must be available for portable operation, according to Technical Requirements paragraph C.3.2.2.

- Sufficient heat must be delivered to each of 3 heat exchangers, in keeping with Technical Requirements paragraphs C.3.2. and C.3.2.2.

- The exhaust discharge acoustic noise level must be in the limits set by MIL-STD-1474B, as per Technical Requirements paragraph C.3.2.9.

- Hot spots are to be minimized and safety guards provided to prevent injury, in compliance with Technical Requirements C.3.2.15.

- Hot surfaces should not damage any adjacent components.

- The exhaust outlet should be located independent of the ventilation air inlet to meet Technical Requirements paragraph C.3.2.10.

5.7.2.6. Burner sealing.

- The burner for each heat exchanger must match the heat and power module (HPM) combustion chamber (see par. 5.8.1).

- The burner-combustion chamber seal must be leak-proof when the HPM and heat exchanger are clamped together, in accordance with Technical Requirements paragraph C.3.2.15.

- The burner-combustion chamber seal must withstand exposure to operating temperatures without seizing.

- The burner-combustion seal must not require any special tools, as given in Technical Requirements paragraph C.3.2.11.

5.7.2.7. Heater packaging (physical).

- The heat and power module (HPM), when attached to a particular heat exchanger, must fit within the volume required for the heaters shown on Drawing 11669489 or 11669490, as given in Technical Requirements paragraph C.3.2.12.

- The combined HPM-heat exchanger unit must weigh less than 40 lbs, in accordance with Technical Requirements paragraph C.3.2.12.

- Hot spots are to be minimized, with safety guards provided, as given in Technical Requirements paragraph C.3.2.15.

- All surfaces to be smooth, and all sharp and/or jagged edges to be rounded.

- All heater electronics must be protected from heat, electromagnetic interference (as per MIL-STD-461B and MIL-STD-462), and shock and vibration (MIL-STD-810) in accordance with Technical Requirements paragraphs C.3.2.9 and C.3.2.10.

- The heater must be, as far as possible, resistant to chemical agents and decontamination solutions, according to Technical Requirements paragraph C.3.2.14.

- The heater must be constructed such that all subsystems are readily accessible, with no special tools being required for maintenance in keeping with paragraph C.3.2.11.

5.7.2.8. Heater packaging (operational).

- Heater operation and maintenance manuals must be provided to facilitate operator training.

- The heater must be constructed to permit portable operation, as outlined in Technical Requirements paragraphs C.3.2.21 and C.3.2.22.

- The heat and power module must be adaptable to 3 types of heat exchangers as given in paragraph C.3.2.

- All clamps, clasps, and connections must be readily accessible and designed in keeping with MIL-STD-1472.

- The heat and power module and heat exchangers must be designed to withstand shock and vibration (as per MIL-STD-810), as given in Technical Requirements paragraph C.3.2.10.

- The heater, when operating, must be low in acoustic noise to meet MIL-STD-1474B as per Technical Requirements paragraph C.3.2.9.

- The heater must be readily maintainable without special tools in accordance with Technical Requirements paragraph C.3.2.11.

- The heater must have a standard military finish in olive green.

5.7.3. Electrical.

5.7.3.1. Control panel.

- The control panel indicators are to be self-explanatory in depicting heater status.

- The panel controls must be easy to use and be accessible according to MIL-STD-1472.

- The heater is to be designed for one-switch operation from the control panel, to meet Technical Requirements paragraph C.3.2.22., and in compliance with MIL-STD-1472.

- The control panel electrical circuits are to be electrically protected by a replaceable fuse, readily accessible and requiring no special tools, in keeping with Technical Requirements paragraph C.3.2.11.

5.7.3.2. Heater control.

- The heater start-up logic must accommodate variations in ambient temperature, fuel type, and fuel pressure, according to Technical Requirements paragraphs C.3.2.1., C.3.2.2., C.3.2.5., and C.3.2.8.

- The heater start-up logic must switch the heater to internal power when sufficient power is generated in order to prevent excessive discharging of the external battery.

- The control logic must regulate the output temperature for the personnel compartment heater and coolant preheater, as given in Technical Requirements paragraph C.3.2.2.

- The heater controls must be "hands-free" and must meet the requirements of MIL-STD-1472.

- The heat and power module shall have emergency shutdown capability for electrical circuit protection, in accordance with Technical Requirements paragraph C.3.2.13.

- The heat and power module shall have emergency shutdown capability for overheat protection, in accordance with Technical Requirements paragraph C.3.2.13.

- The heat and power module shall have emergency shutdown capability for excess power level protection, in accordance with Technical Requirements paragraph C.3.2.13.

- The heat and power module shall have emergency shutdown capability for insufficient power level protection, in accordance with Technical Requirements paragraph C.3.2.13.

5.7.3.3. Control packaging.

- The control system electronics must be packaged such that they are not subject to electromagnetic interference, in accordance with MIL-STD-461B and MIL-STD-462, as per Technical Requirements paragraph C.3.2.9.

- Individual control system electronics boards must be coated to resist salt, dust, sand, humidity, and chemical agents and decontamination solutions (as per Technical Requirements paragraph C.3.2.14.).

5.7.3.4. External power connections.

- Connections are required for providing output power from the heat and power module (HPM) to the coolant circulation pump.
- Connections are required for start-up power for the HPM.
- Connections are required for providing power to an electrically operated fuel pump.
- Military standard connections are to be used, and are to be in accordance with MIL-STD-1472.
- All electrical connections must not require special tools, according to Technical Requirements paragraph C.3.2.11.

5.7.3.5. MS type connectors.

- Connectors to deliver output power from the heat and power module (HPM) must be provided.
- All connections must not require special tools, according to Technical Requirements paragraph C.3.2.11.
- All connection cable connectors are to be designed according to MIL-STD-1472.

5.7.3.6. Connection locations.

- All connections are to be located so as to minimize the lead lengths.
- All connections are to be oriented similar to those for existing heaters shown on Drawings 11669489 and 11669490, as per Technical Requirements paragraph C.3.2.12.
- All connections are to be easily accessible when the HPM is in place and shall require no special tools (Technical Requirements paragraph C.3.2.11.).
- All connections must not interfere with existing vehicle fittings and equipment.

5.8. Conceptual System Description

5.8.1. General. The heater system shall consist of a personnel heat exchanger, a coolant heat exchanger, a portable heat exchanger, and a heat and power module (HPM). The HPM shall be constructed so that it can be interchanged with any of the heat exchangers and shall connect to the respective burner and combustion air ducts, as well as connect with an external electrical supply for start-up power. A single heater shall consist of an individual heat exchanger connected to the HPM.

Summaries of the thermal and electrical requirements are given in Tables 5-7 and 5-8 for these subsystems, with Figure 5-3 being a block diagram showing their relative locations.

5.8.2. Heat and Power Module. The HPM shall consist of a thermoelectric converter (TEC) to produce electrical power, a liquid fuel burner system, a fuel regulation and delivery system, an air circulation and combustion air delivery system, and a control system.

The HPM shall provide a maximum of 100 W net external power for operating the electrically-operated fuel pump and an electrically-operated coolant circulation pump, when either or both are required. It shall also provide 100,000 BTU/hr for heating of the TEC and for heat delivery. It shall have universal connections for its heat and power outlets and shall have an external connection for start-up power. Provision shall be made to modulate the heat delivered by the individual heat exchangers and power produced by the TEC.

The HPM shall be portable and electrically self-sustaining, providing power to the liquid fuel burner, control system, and fuel pump (when the latter is required). When attached to an individual heat exchanger, the combined unit shall weigh less than 40 lbs and shall be within the size restriction outlined for the existing 60,000 BTU/hr heaters shown on Drawings 11669489 or 11669490.

The maximum TEC power output shall be 300 W, with 200 W required to operate the HPM only in all heating modes. The amount of useable heat from the HPM is independent of the TEC conversion efficiency. For example, a low conversion efficiency TEC will require more heat but the air circulating fan will capture that heat which is not converted into electricity.

The personnel and coolant heating modes will use an external electrically-operated fuel pump which requires approximately 50 W for operation. The air circulation and combustion air delivery system shall have a single drive motor which will require an estimated 150 W (see par. 5.9.10.). The logic control and system monitor for HPM subsystem operation will require 10 W.

The HPM electrical system will operate on a dual-voltage arrangement. (See the description of the electrical control system and start-up sequence in par. 5.9.3.) This is required as the best TEC performance is at a nominal 12 VDC, while the external battery used for start-up is at 24 VDC nominal.

During start-up, the nominal 24 VDC is used to operate the control logic, ultrasonic atomizer, external fuel pump (if used), and igniter. The 28 --> 4 VDC DC/DC voltage converter is used to power the drive motor for the air circulation fan and combustion air blower during start-up (see par. 5.9.10.). Normally, this motor will operate at 12 VDC, which is the most

Table 5-7. Heat and Power Module Thermal and Electrical Summary

HPM Subsystem	Maximum Heat Output (BTU/Hr)	Maximum Power Produced (W)	Maximum Power Consumed (W)
Thermoelectric Converter	11,525	300	-
Combustion	-	-	25
Air Circulation and Combustion Air	-	-	150
Exhaust	87,440	-	-
Fuel Delivery	-	-	50
Logic Control & Monitoring	-	-	10
DC/DC Conversion Losses (90% DC/DC Conversion Efficiency)	-	-	15*
Coolant Pump	-	-	50**
Maximum Total	98,965	300	300

* DC/DC conversion is only necessary to operate 28 VDC items, during steady state conditions.

**Coolant pump is operated only with the coolant preheater. In other heating modes excess power will be available.

Table 5-8. Heater Thermal and Electrical Requirements

	Available Heat (BTU/Hr)*	Output Heat (BTU/Hr)	Maximum Exchanger Efficiency (%)	Total Heater Power Consumption (Watts)
Personnel Heater	98,965	60,000	61	250
Coolant Heater	98,965	30,000	30	300
Portable Heater	98,965	40,000	40	200**

* Sum of available heat from thermoelectric converter cooling fins and heat remaining in combustion chamber.

**Does not include 50 Watts for fuel pump; fuel delivery is via a pressurized container (3-15 psig).

efficient, since the TEC can provide this voltage directly to it without any conversion losses.

During steady-state operation, the 12 VDC from the TEC will be converted to 28 VDC to allow the control system, fuel pump, and ultrasonic atomizer to operate as required (see Table 5-10 and par. 5.9.3.).

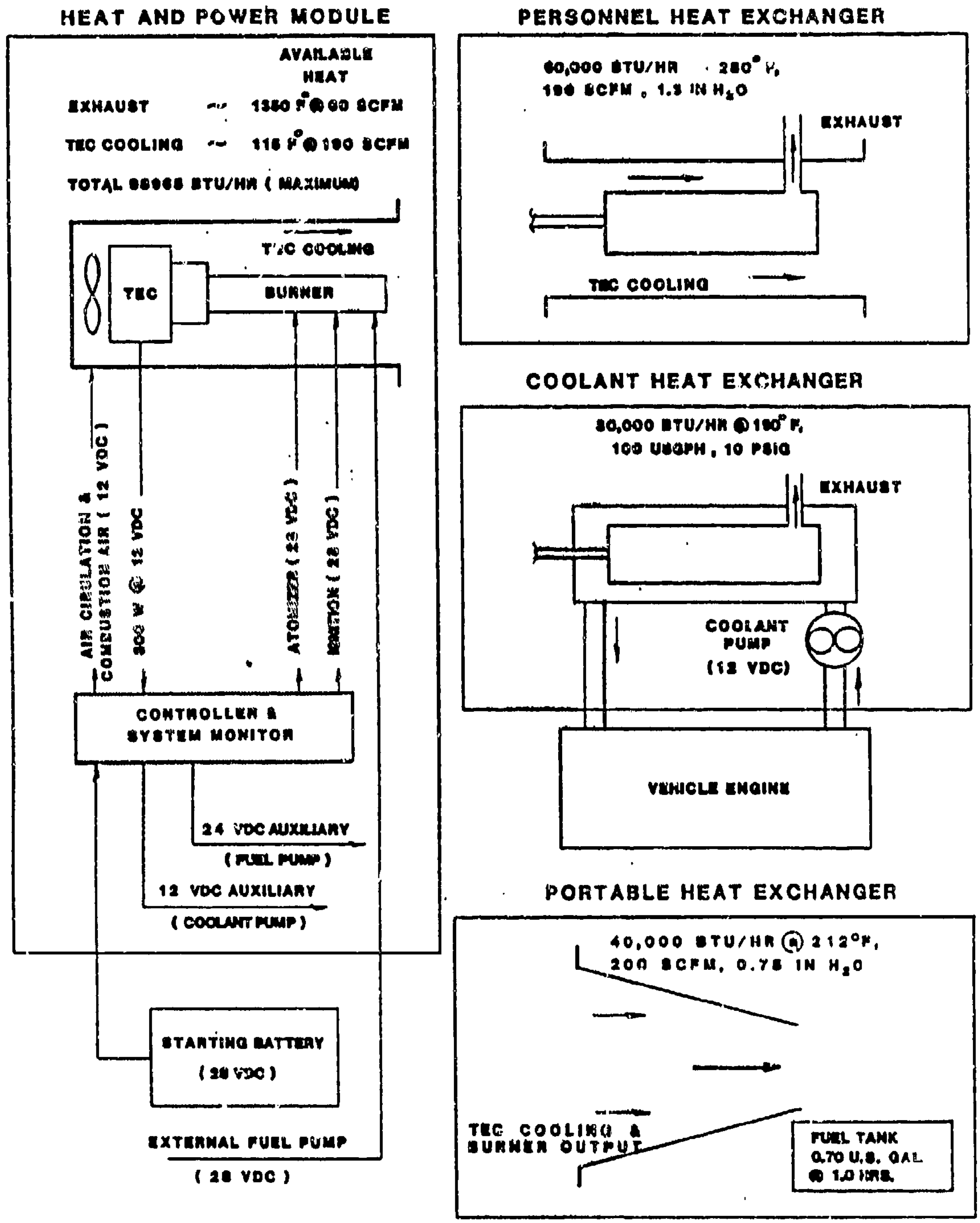
The burner subsystem shall consist of a combustion chamber, a combustion air blower, a liquid fuel atomizer, burner (permanently attached to the heat exchanger being used, as per pars. 5.9.4., 5.9.7., 5.9.8., and 5.9.9.), a fuel regulator, and an ignition system for start-up. The burner subsystem is rated for a nominal output heat of 100,000 BTU/hr or 5 lb/hr of fuel and must be self-sustaining after stable combustion has been achieved. The heat shall be used for operating the TEC and the heat exchangers. It is estimated that the available heat released by the burner exhaust and TEC cooling fins will have a theoretical maximum of 98,965 BTU/hr.

The ignition system of an individual heater shall consist of an igniter and two spark plugs. The igniter circuit remains on the HPM while the spark plugs are threaded into the burner, which is part of the exchanger. Spark plugs were selected on the basis of previous experience with low-temperature ignition of diesel fuel.

Spark plugs require less energy to initiate combustion than do glow plugs and are not subject to overheating. A cold battery would have less energy than it would at room temperature and may not provide sufficient current to initiate combustion if high-current devices such as glow plugs are used for ignition. Also, the igniter is constantly on during the initial start-up phase only to allow re-lighting in case of flame-out due to irregular fuel flow caused by, say, air bubbles in the fuel supply line. Glow plugs can be damaged or severely corroded from the combined effects of electrical and combustion heating. Once steady combustion has been established, the burner is at the auto-ignition temperature and the igniter shut off.

The combustion air blower will be a centrifugal unit, and air circulation provided by an axial fan. They will be driven by the same motor, which will operate between 4 VDC at start-up and 12 VDC at full TEC power and consume an estimated 150 W (see par. 5.9.10.). The fuel for the personnel heater and coolant preheater will come from an external electrically-operated pump, which will require an estimated 50 W at a nominal 24 VDC, and will be delivered to the atomizer by the fuel regulator system. The portable heater fuel supply will be a detachable pressurized tank (see par. 5.9.11.). The liquid fuel atomizer (the ultrasonic unit chosen in par. 5.5.2.) will require an estimated 20 W with an additional 5 W to power a normally closed fuel line solenoid valve (see pars. 5.9.2., 5.9.3., and 5.9.5.). All subsystems shall be operable over the ambient temperature range of -65°F to +70°F in any mounting position.

The control system shall consist of start-up logic and system monitoring, and shall have provision for operating the DC/DC voltage converters mentioned earlier. The start-up logic shall have the capability to operate



TEC = THERMOELECTRIC CONVERTER

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FIGURE 5-3. HEATER CONCEPTUAL BLOCK DIAGRAM at 28 VDC from an external battery for HPM starting, switching to the internally-generated 28 VDC after stable operation has been achieved. It shall also have provision for emergency shutdown and shall have the capability to detect combustion failure.

The HPM shall be operable over the ambient temperature range of -65°F to +70°F, and have provision for system start-up in these conditions. The performance of the ultrasonic atomizer and ignition system must also be able to cope with the ambient temperature range. Since the heater must have multifuel capability over this temperature range, the logic control must also compensate for changes in fuel viscosity.

After stable combustion has been achieved, the logic control shall adjust the HPM power output to a level sufficient for self-sustained operation and to meet the specific heater requirements. Output power will vary with output heat. As more heat is required, the HPM will respond by producing more power. At the higher ambient temperatures, less heat will be released and, therefore, less power produced. This appears to be acceptable because if less heat is required, then less power will be needed for self-sustained operation.

5.8.3. Personnel Heat Exchanger. The personnel heat exchanger shall consist of an exhaust gas-to-air heat exchanger, an igniter, and a liquid fuel burner. It shall deliver 60,000 BTU/hr to the compartment at a temperature of 280 ± 20°F over the ambient temperature range of -65°F to +70°F. The atomizer, combustion air delivery and igniter driving circuit are part of the HPM and will be connected to the personnel heat exchanger.

When the HPM is attached to the heat exchanger, the combined unit shall weigh less than 40 lb and shall be within the size limits for the existing 60,000 BTU/hr heaters shown on drawings 11669489 or 1169490.

The air circulation fan shall provide cooling air to the TEC and heated air to the personnel compartment. The minimum discharge from the heater shall be 190 SCFM at a static pressure of 1.3 in. water, the temperature being 280 ± 20°F.

The heat exchanger is required to have a nominal exhaust gas back pressure of 0.85 in. water, with the outlet air temperature at 280 ± 20°F in order to deliver the required heat. It is required that the heat exchanger fit or be adaptable to the existing ductwork in the vehicle.

It is also required that the combustion air supply for the HPM be independent of that for compartment ventilation in order that the heater (that is, the HPM and heat exchanger together) can be operated in an NBC environment.

5.8.4. Coolant Heat Exchanger. The coolant heat exchanger shall consist of an exhaust gas-to-liquid heat exchanger, spark plugs, a liquid fuel burner, and a coolant circulation pump. It shall deliver 30,000 BTU/hr to the vehicle engine at a maximum coolant temperature of 190°F over the ambient temperature range of -65°F to +70°F. It shall have connections for the combustion air, and ignition power.

The coolant pump shall deliver a maximum of 100 USGPH at a 10 psig head. Suppliers contacted recommended a gear pump to be best suited for this application. It is self-priming and will operate reliably in any mounting position. Its estimated power consumption is about 50 Watts at 12 VDC.

The heat exchanger shall have a nominal exhaust gas back pressure of 0.85 to 1.0 inch water and the maximum coolant outlet temperature shall be 190°F in order to deliver the required heat.

5.8.5. Portable Heat Exchanger. The portable heat exchanger shall consist of an outlet nozzle, spark plugs, and a liquid fuel burner. The burner exhaust gas shall be diluted with sufficient ambient air from the air circulating fan to reduce the carbon monoxide concentration to below 400 ppm and maintain the oxygen concentration above 12 percent.

The heater shall deliver 40,000 BTU/hr at a temperature of 212°F and outlet pressure of 0.75 in. water over the ambient temperature range of -65°F to +70°F. It shall have connections for the combustion air and ignition power.

When the HPM is attached to the heat exchanger, the combined unit shall weigh less than 40 lb. and shall be within the size limits for the existing 60,000 BTU/hr heater shown on drawings 11669489 or 11669490.

As the heater (consisting of the portable heat exchanger and the HPM) is to be portable, it must have capability for self-sustained operation for one hour, including its own independent fuel supply. The heater will require an external battery for start-up, and shall be designed to permit hand-held operation.

5.9. Heater Subsystem Description

5.9.1. Thermoelectric Converter.

5.9.1.1. Principles of operation. A thermoelectric generator is an array of thermocouples which produce electrical power when heated. The amount produced is dependent upon a number of factors, including the temperature of the heat source, thermocouple materials used, and the number of thermocouples available.

Figure 5-4 illustrates the operation of a thermoelectric converter. An individual thermocouple consists of a hot electrode (commonly called a "hot strap") which is on the heated side, a cold electrode (commonly called a "cold strap") which is on the side from which the heat not converted into power is rejected, and two thermoelectric segments. These segments (commonly called "legs") are made from either an "N" semiconductor material (in which the current produced flows away from the heated side) or a "P" semiconductor material (the current flowing towards the heated side). A

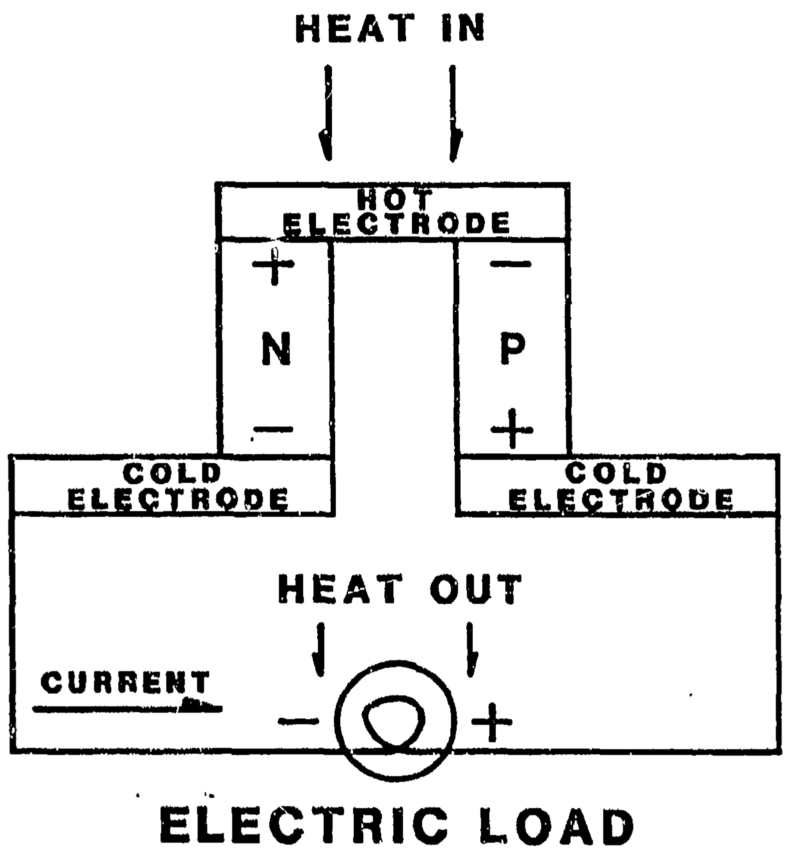

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FIGURE 5-4. THERMOELECTRIC CONVERTER OPERATION couple requires one leg made from each material. In a converter, the "N" legs are connected electrically in series to the "P" legs. The circuit is completed by connecting the couple array to an external load.

Legs can be made from several materials, with commercial development concentrating on bismuth telluride (Bi_2Te_3), lead telluride (PbTe), and silicon germanium (SiGe) base materials. Various other elements are used as dopants. Figure 5-5 shows the approximate temperature ranges where each alloy is effective.

In addition to operating temperature, the thermoelectric efficiency (the ability of the material to convert heat into electricity) is another major factor to be considered in selecting a leg material. This is given by the figure of merit, Z, which is defined as:

$$Z = \frac{S^2}{\rho k},$$

where:

S = Seebeck coefficient of leg material,
ρ = electrical resistivity of leg material,
k = thermal conductivity of leg material.

The Seebeck coefficient is a measure of the voltage produced by a material for a given temperature differential (see par. 5.2.2.1.). This is independent of leg geometry, but varies with temperature (see Figure 5-6). This temperature variation for the 3 basic materials appears in Figure 5-7[49].

It should be noted that when comparing the figure of merit of at least 2 materials, the units used are $°K^{-1}$. Power, on the other hand, is dependent upon a leg's geometry (specifically, the ratio of the length to the cross-sectional area).

The material life expectancy must also be accounted for. Commercial grade PbTe has been used in field applications for over 20 years, with minimal degradation (averaging 0.2% per year). This material has a conversion efficiency of about 8%, meaning that approximately 8% of the heat passing through the legs is converted to electricity. For military applications where the ratios of power to weight and power to volume are important issues, a more efficient material is used that is about 9.5% efficient with a peak Z of 0.00165. These materials, however, are used with a sacrifice in life expectancy (10,000 to 20,000 hours). Materials having conversion efficiencies of 11% have been made but they usually demonstrate a much shorter life time. An efficiency of 8% corresponds to a Z value of 0.00144 and experimental materials are regularly produced with Z values close to 0.002. This is an increase of 35% over commercial materials and 20% over military materials. These materials are experimental with very little data on life expectancy and degradation rates available. It is expected that degradation can be controlled and that these experimental materials will be

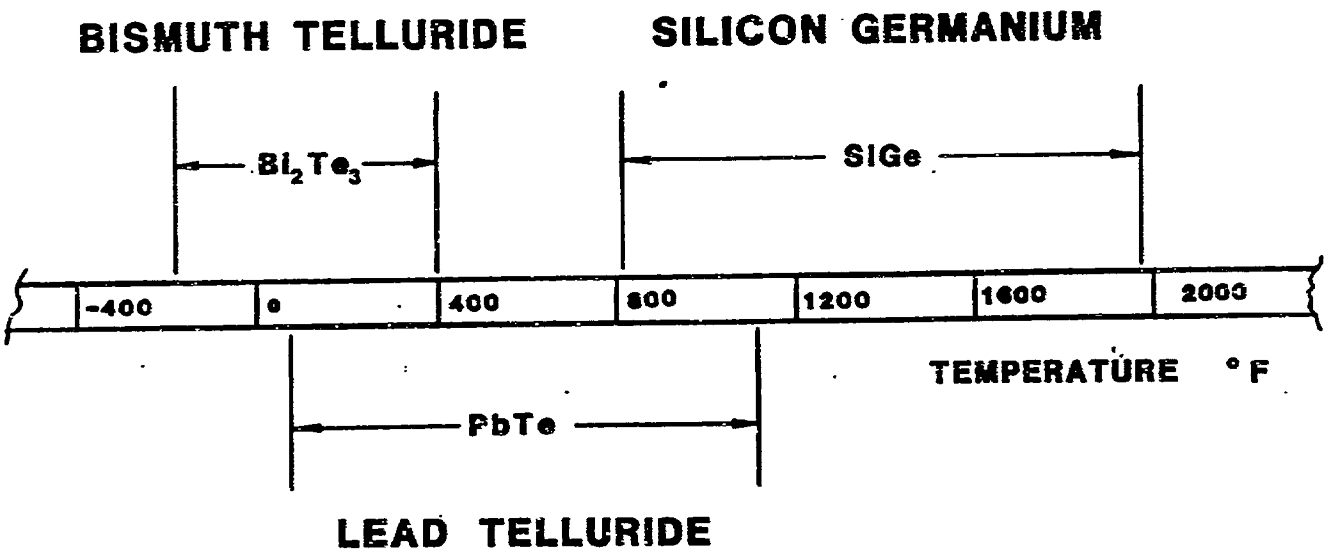

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FIGURE 5-5. THERMOELECTRIC MATERIAL TEMPERATURE RANGE

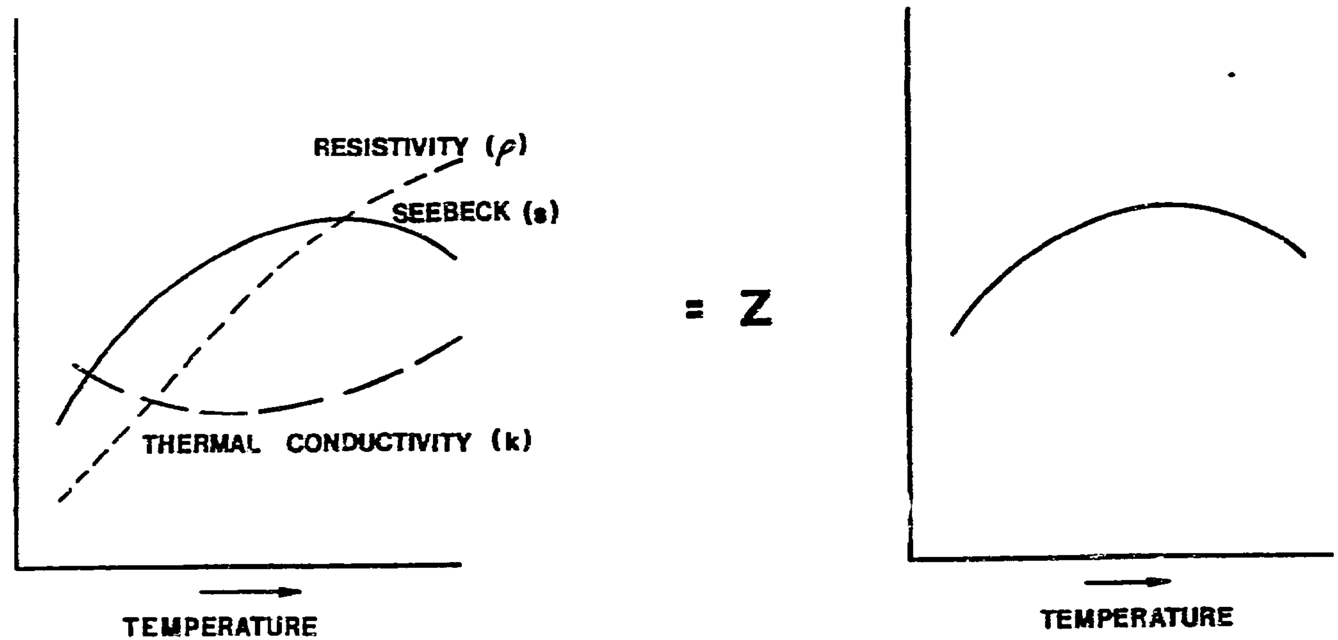

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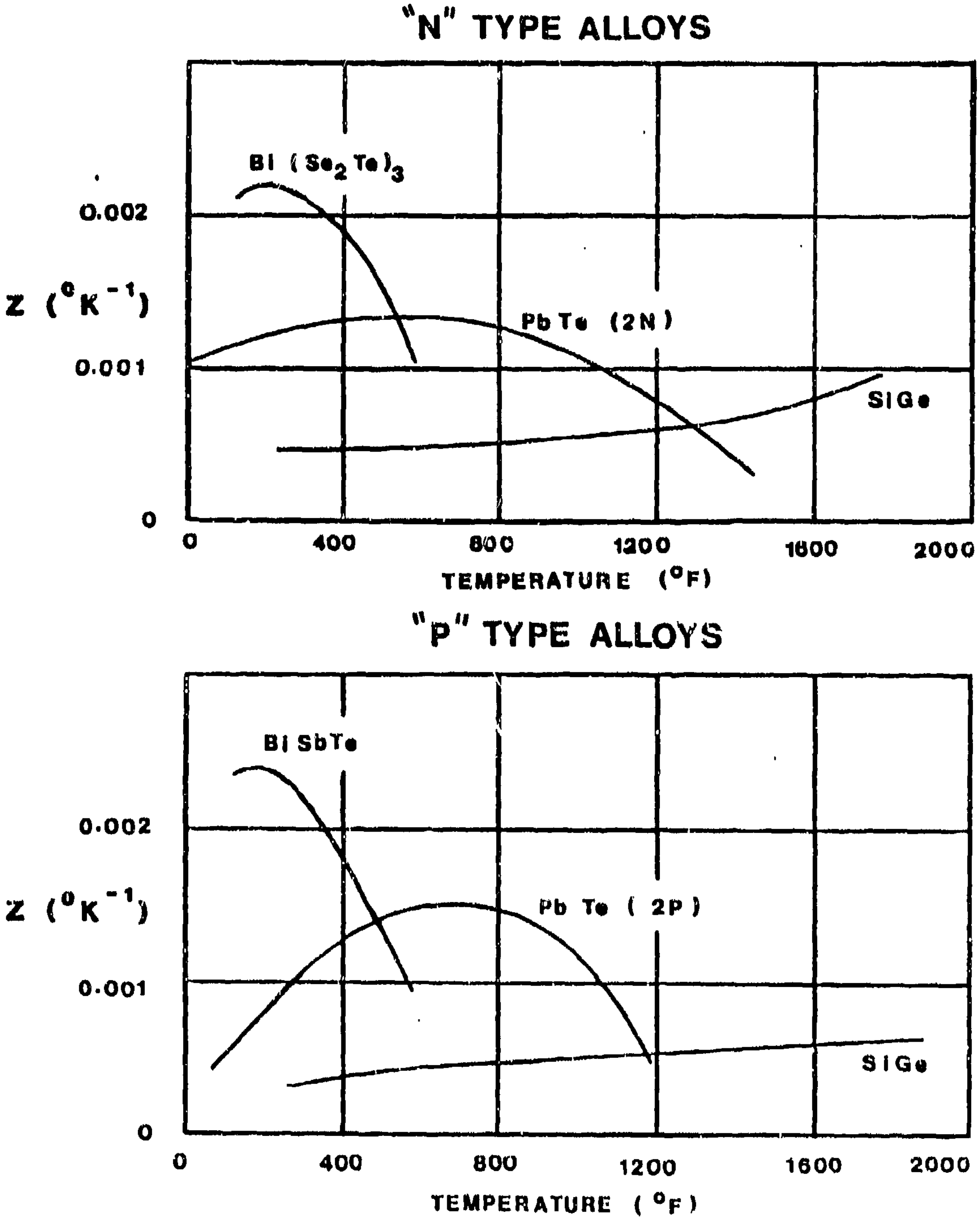
FIGURE 5-6. TYPICAL THERMOELECTRIC MATERIAL PROPERTY TEMPERATURE VARIATION



NOTE: FIGURE BASED ON DATA FOUND IN[49] TACOM 7000-7-1

FIGURE 5-7. FIGURE OF MERIT TEMPERATURE VARIATION FOR PRESENT THERMOELECTRIC MATERIALS

ready to be manufactured in the near future. There are also indications that materials superior even to these are attainable.

5.9.1.2. Thermoelectric converter. The thermoelectric converter which will be used to provide internal power to the HPM after start-up is shown in Figure 5-8. A radial design was chosen for a number of reasons. The available space for the heater is approximately a cylinder more than 12 in. in diameter by 27 in. long, and a radial converter would make more efficient use of this volume. As a result, it can be built around the circumference of the combustion chamber of the burner. Since circulating air would be moved parallel to the axis of this cylinder, the converter can be easily cooled and the heat recovered for recirculation.

The converter assembly consists of a combustion chamber, the thermoelectric elements and assembly (described in par. 5.9.1.3.), thermal insulation, a converter cold side shell, converter cooling fins, 2 insulation fill tubes, and 2 electrical power terminals.

The combustion chamber contains the flames from the reactions in the burner. The thermoelectric converter is built around it and receives the heat that is radially transferred. The elements (i.e., the thermocouple arrays described in par. 5.9.1.1.) produce electricity through this heating, and the temperature gradient required for maximum power is maintained by holding the cold side shell temperature constant relative to ambient. This heat is removed by circulating air past the fins, which are attached to the external shell. The electricity generated by the thermocouples passes to the external circuitry by way of the power terminals. Thermal insulation is placed inside the converter shell after it is assembled during processing to reduce shunt heat losses. In order to prevent deterioration of the leg material due to prolonged exposure to high temperatures, an inert gas is inserted and the fill tubes are pinched shut to maintain the hermetic seal.

The converter shown is designed to produce 300 W of electrical power at 12 VDC from an input heat of about 12,560 BTU/hr (3,680W). This would correspond to a combustion chamber temperature of about 1,150°F and a fin base temperature of 245°F. This power will be produced by 100 thermocouples arranged into 20 blocks of 5 couples each.

5.9.1.3. Thermoelectric elements and assembly. An exploded view of the proposed thermoelectric assembly block is shown in Figure 5-9.

The converter is designed to be electrically in series and thermally in parallel. Heat from the combustion chamber is received by the hot straps. To prevent short-circuiting of adjacent couples by having the current flow through the combustion chamber wall, a dielectric layer separates the wall from the hot straps. This can be made from a number of electrically insulating materials although a low coefficient of thermal expansion and high thermal conductivity are desirable.

The hot straps are made from copper bonded to iron and fitted with a layer of tungsten. The copper is a good thermal and electrical conductor while

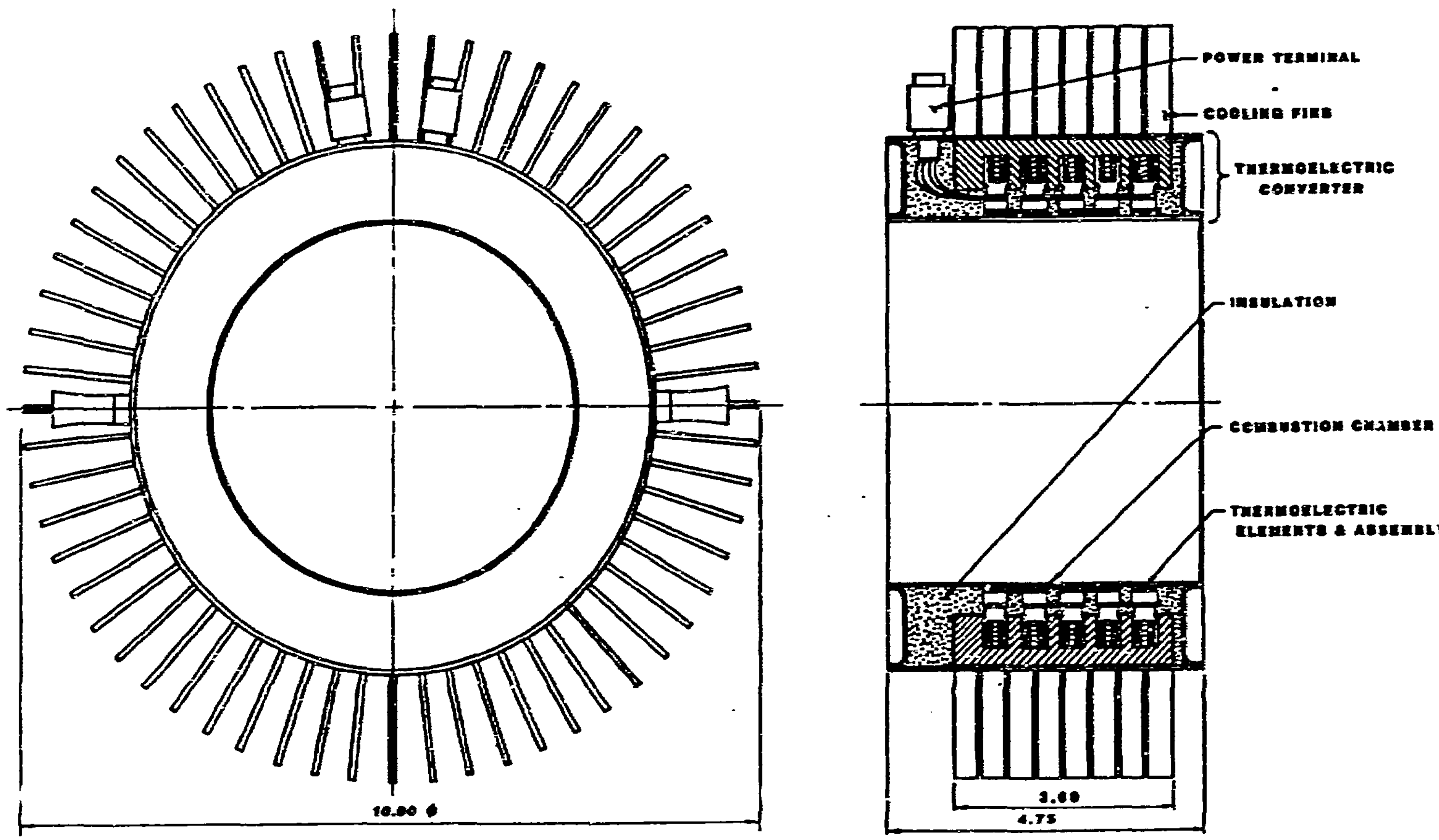


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FIGURE 5-8. 300 WATT THERMOELECTRIC CONVERTER

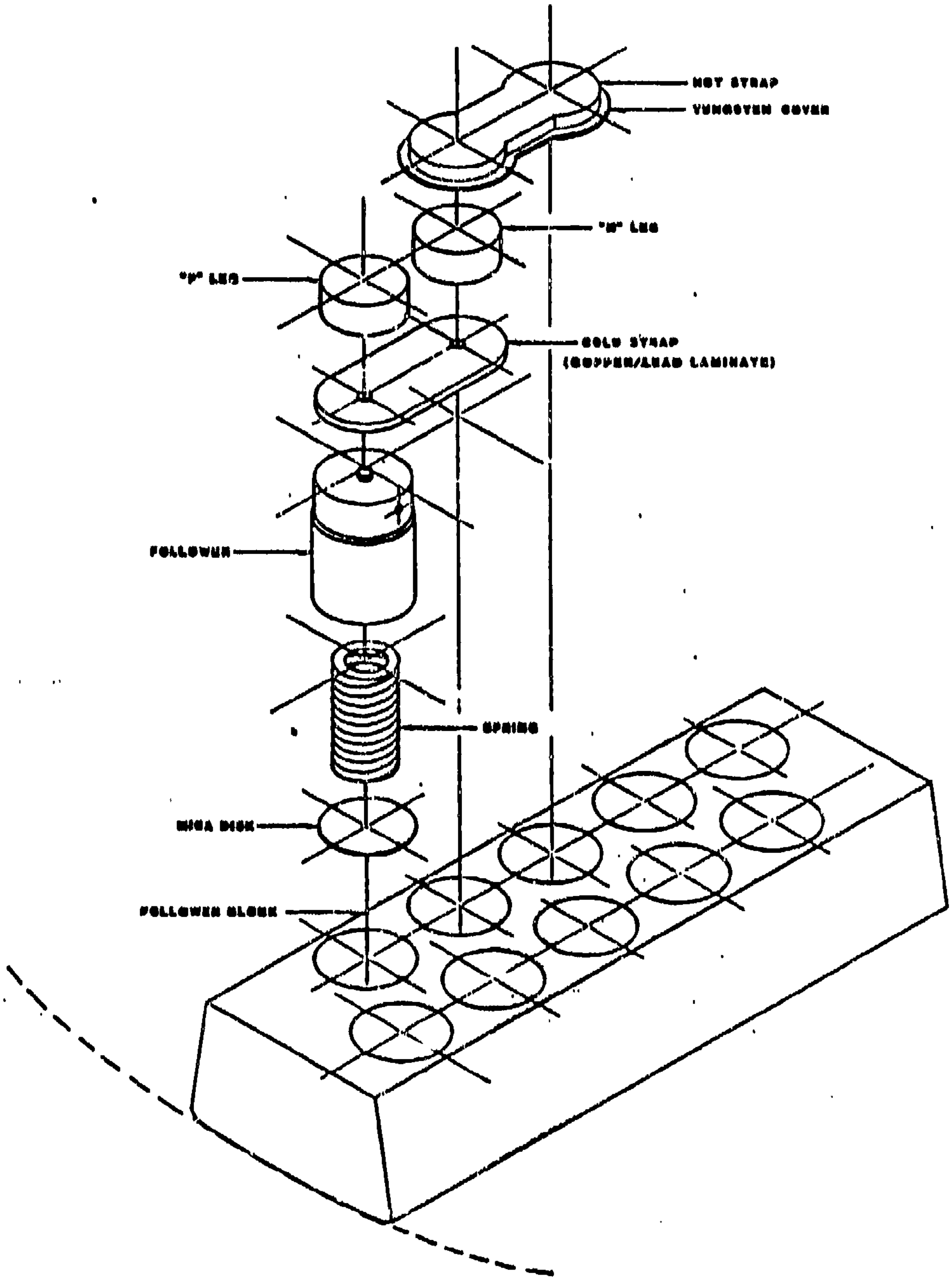

FIGURE 5-9. THERMOELECTRIC ASSEMBLY AND ELEMENTS

the iron provides rigidity to the strap and prevents the copper from undergoing plastic deformation. The tungsten acts as a barrier to prevent the iron from diffusing into the legs and contaminating them, thereby reducing the converter lifetime. Often the legs will be set into a mica sheet which prevents iron from migrating around the tungsten.

The legs are located next to the tungsten. The "N" leg of one thermocouple is electrically connected to the "P" leg of the adjacent one by means of a cold strap and a layer of lead between the strap and leg. The cold strap is made from copper and can be either a solid piece or a number of thinner pieces separated by lead. The lead serves to bond the cold straps to the leg and does this by being allowed to plastically deform during part of the thermoelectric converter fabrication process.

It is essential that good thermal contact between the combustion chamber and the hot straps be maintained. For this purpose, the legs are kept under load by compression springs, one per leg. The load is transmitted from the spring to the leg through the follower, which is bonded to the cold strap with lead. The springs and followers are held in place by the follower block. As the block is coated with a dielectric material, a mica disc is in place between the spring and the block to prevent damage to this coating. When the outer converter shell is put into place, the springs are compressed and exert the necessary force to provide good thermal contact at the cold side and hot side.

If the cold strap is a solid piece, the lead used to bond it to the "P" leg and to the follower is metallurgically bonded to the copper. This is done as a cost-reduction measure as less labour would then be required to assemble the thermoelectric converter. Laboratory tests have shown that cold straps made in such a manner are as rugged and durable as those made from thin pieces of copper separated by lead.

Examples of this system can be seen in Figures 5-10 and 5-11.

5.9.1.4. Cost reductions. Thermoelectric device design and practical implementation has been characterized by the conventional spring-follower system, as illustrated in Figures 5-9 and 5-11, since the early 1960's. This system is the standard construction used by a number of thermoelectric generator manufacturers. The spring-follower system is well proven and operable, but there is considerable work under way to optimize device construction. Since the 1960's, many technical achievements have occurred that are useful towards improving the conventional spring-follower system.

Conventional construction must employ a thermal grease on the sliding interface between the followers and the mating holes in the follower block. This thermal grease must be used to enhance the conduction of the heat from the hot side of the thermoelectric converter, through the thermoelectric segments and through the cold side of the converter, where it is rejected to the atmosphere. However, the grease contains a great deal of oily solvents which must be removed from the hermetic enclosure by processing to avoid contamination of the thermoelectric elements during operation of the

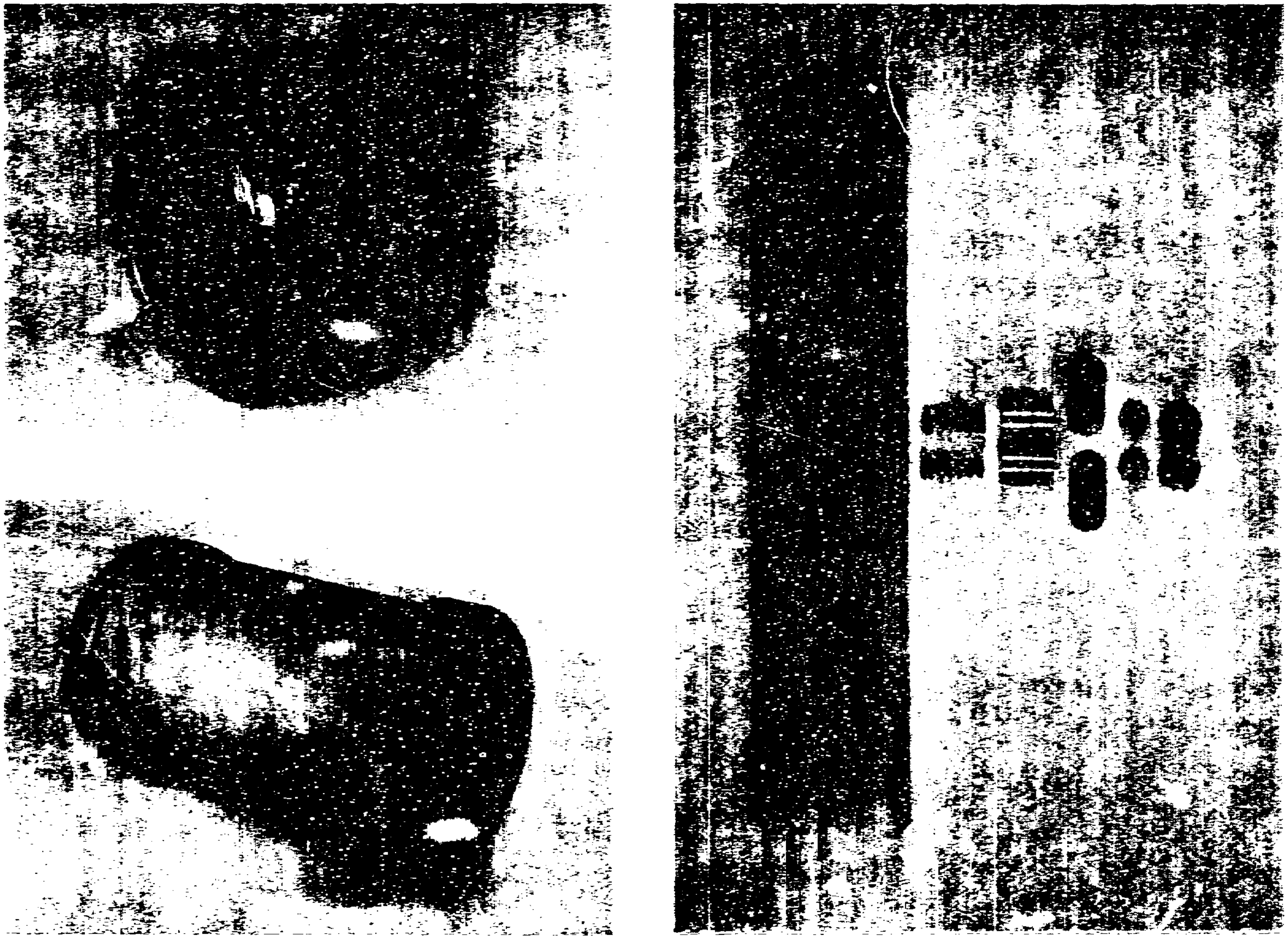

Figure 5-10. Typical Radial Thermoelectric Converter

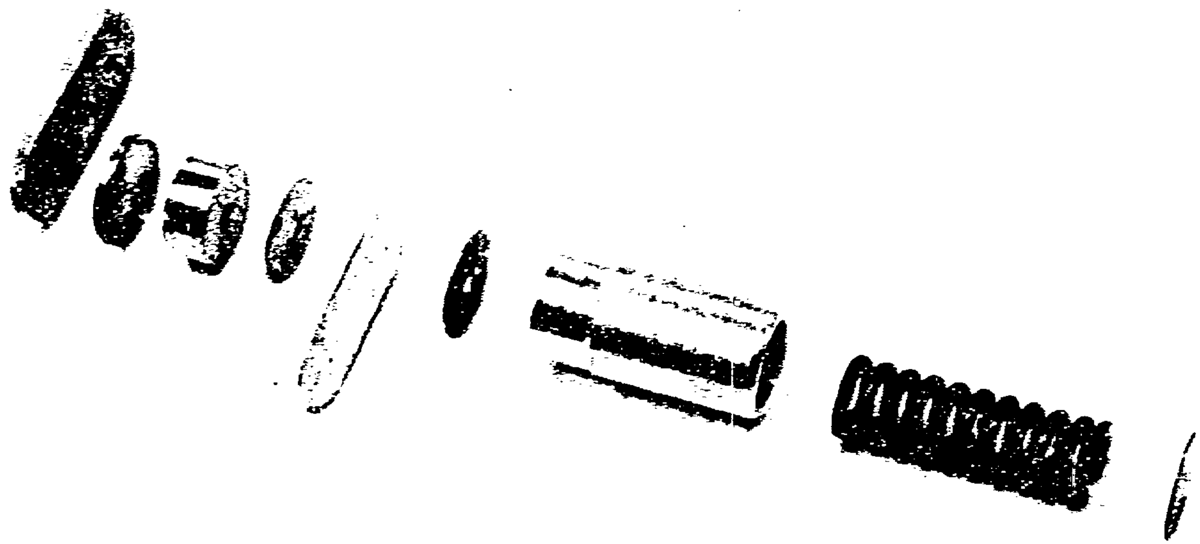

Figure 5-11. Typical Spring-Follower Assembly

generator. These segments are very sensitive to oxidation and contamination at operating temperatures, and performance of the converter hinges directly on the purity of the atmosphere within the hermetic enclosure. This necessitates even longer process times, requiring longer vacuum pump times and more inert gas flushes than would be the case in the same volume without the grease.. A thermoelectric converter construction eliminating the need for grease within the hermetic enclosure would be lower in cost, because the process time required for such a converter is reduced by the absence of thermal grease.

The development of this type of construction over the last 3 years has been effected by the use of test units (Figure 5-12). The units allow for quick assembly and disassembly of a hermetic environment in which test configurations of the lower-cost construction can be carried out. These test units are fully instrumented and heated by electric heaters such that all relevant performance data can be recorded by a data acquisition system.

As a result of the extensive work carried out on the test apparatus, two prototype generators (180 Watt) were constructed employing the lower-cost configuration. These prototypes were fully instrumented and tested under a variety of conditions, and are termed Mass Producible Converter (MPC).

Table 5-9 is a cost comparison of the MPC and a conventional flat-plate thermoelectric converter (Figure 5-13). The projected costs are based on existing achievements. Details are proprietary. The cost reductions are significant, and as noted in Table 5-9 manufacturing costs will drop with increased volumes. The costs were based on figures originally given in 1985 Canadian dollars and were adjusted by 5 percent for inflation and an exchange rate of $1.37 Canadian/$1.00 American (as of May 31, 1986).

On the whole, the MPC configuration is the next logical step in thermoelectric device construction. It promises improved performance and, most importantly, lower cost.

5.9.2. Ultrasonic Atomizer.

5.9.2.1. Principles of operation. A liquid fuel burner is effective if the fuel used is completely consumed in the combustion reactions. The purpose of an atomizer is to facilitate this by breaking up the flow into small droplets which will burn easier.

An ultrasonic atomizer accomplishes this by concentrating high-frequency pressure waves in a small section inside the body[50]. The source of these waves is a pair of piezoelectric crystals made from a ceramic material such as barium titanate ($BaTiO_3$). The crystal structure is such that the dimensions change in the presence of an electrical field, allowing electrical energy to be converted into mechanical and vice-versa[51].

In this application, mechanical oscillations (i.e., alternating expansions and contractions) are produced by the crystals by stimulating them with an alternating current[51], with the crystal frequency matching that of the

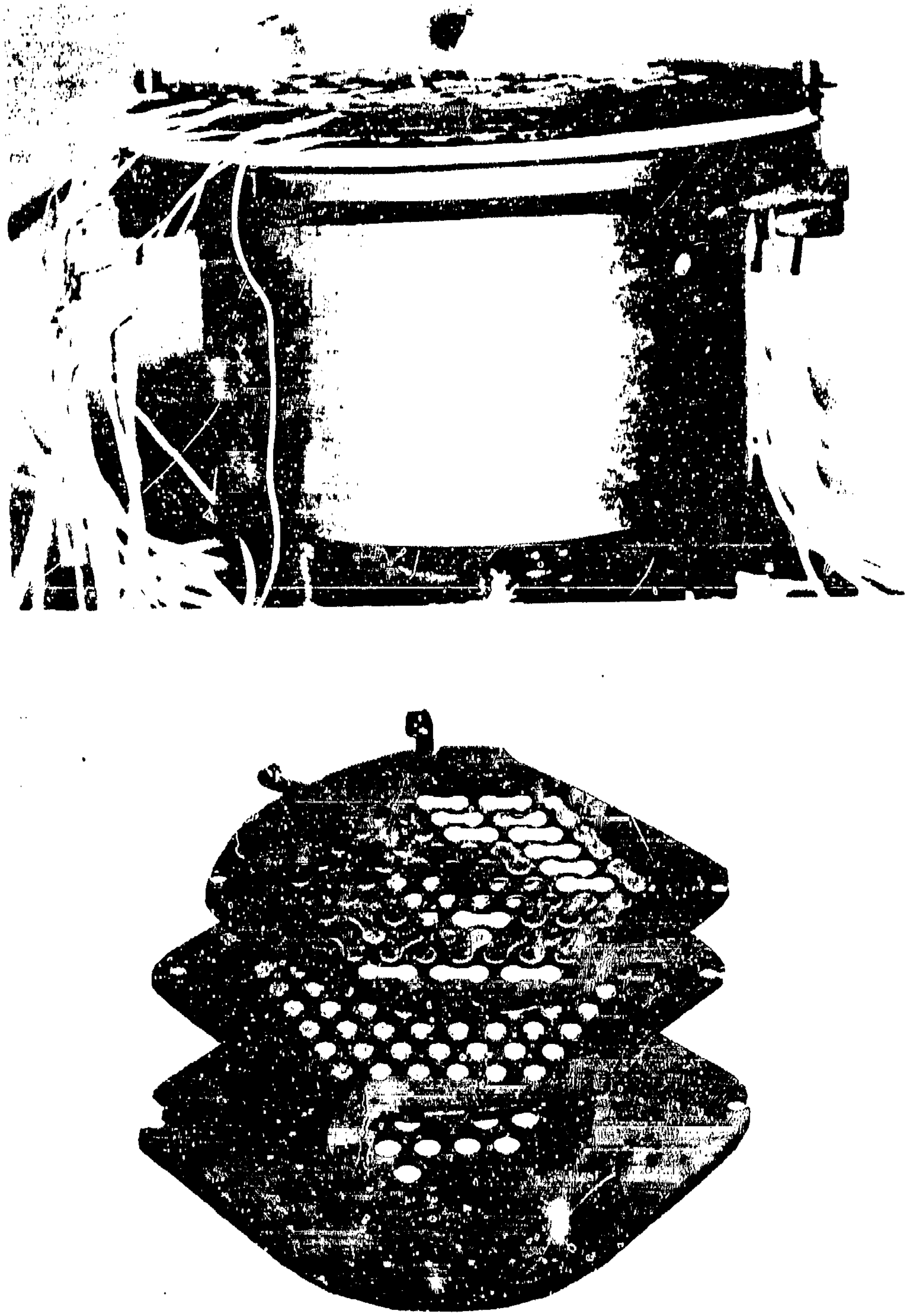

Figure 5-12. Thermoelectric Test Unit

Table 5-9. Cost Comparison of Thermoelectric Converter Configurations

	Conventional Flat Plate (120 W)			MPC* (180 W)		
	QTY REQ	UNIT COST	TOTAL COST	QTY REQ	UNIT COST	TOTAL COST
• Parts						
Combustion Chamber Assembly	1	204.27	204.27	1	112.66	112.66
Thermal Spreader	1	15.67	15.67	--	--	--
Hot Side Insulator (Mica/Kovar)	1	25.46	25.46	1	10.81	10.81
Hot Strap	80	0.90944	72.76	80	0.117	9.32
Hot Cap**	160	0.22456	35.93	80	0.207	16.55
Thermoelectric Elements	160	0.340	54.45	160	0.23	36.79
Lead Discs	320	0.01	3.20	--	--	--
Cold Strap	80	0.15455	11.59	80	0.092	7.36
Followers	160	0.22901	36.64	--	--	--
Springs	160	0.04730	7.57	1	1.72	1.72
Spring Insulators (Mica)	160	--	--	--	--	--
Cold Junction Plate	1	53.30	53.30	--	--	--
Retaining Film	2	1.691	3.38	--	--	--
Power Leads	2	--	--	2	--	--
Heat Rejection Assembly	1	44.44	44.44	1	27.59	27.59
MPC Cold Side Assembly	--	--	--	1	6.22	6.22
Mica Templates	--	--	--	3	0.65	1.95
MPC Housing Assembly	--	--	--	1	6.76	6.76
Weld Back Ring	--	--	--	1	0.19	0.19
Enclosure Ring	1	12.19	12.19	--	--	--
Tubulation Fitting	2	0.41	0.82	1	0.58	0.58
Power Connector	1	59.91	69.91	1	18.39	18.39
Insulation	1,400 gm	0.00635	8.88	140	0.00635	0.89
Misc. Parts (Not included in above)	--	--	105.38	--	--	22.99
• Labor						
Assembly Labor (welded ready for process)	15	10.96	164.78	1.25	10.96	13.70
Process Labor	2	10.96	21.92	0.25	10.96	2.74
Seat-In Labor	1	10.96	10.96	0.50	10.96	5.48
Total Manufacturing Cost			963.50			302.60

Assumptions and Conclusions

1) Quantity of 400 units per year

2) Conventional 120 W flat plate converter cost per watt = $8.03

3) The 180 W MPC equivalent thermoelectric converter cost per watt = $1.68

4) As volumes increase beyond 400 units per year the cost of manufacturing the MPC will decrease at a larger percentage rate than the present products due to being much less labor intensive.

5) Exchange Rate = $1.37 Canadian/$1.00 U.S.

* Mass Producible Converter (Flat Plate Configuration)

** Not applicable to radial design

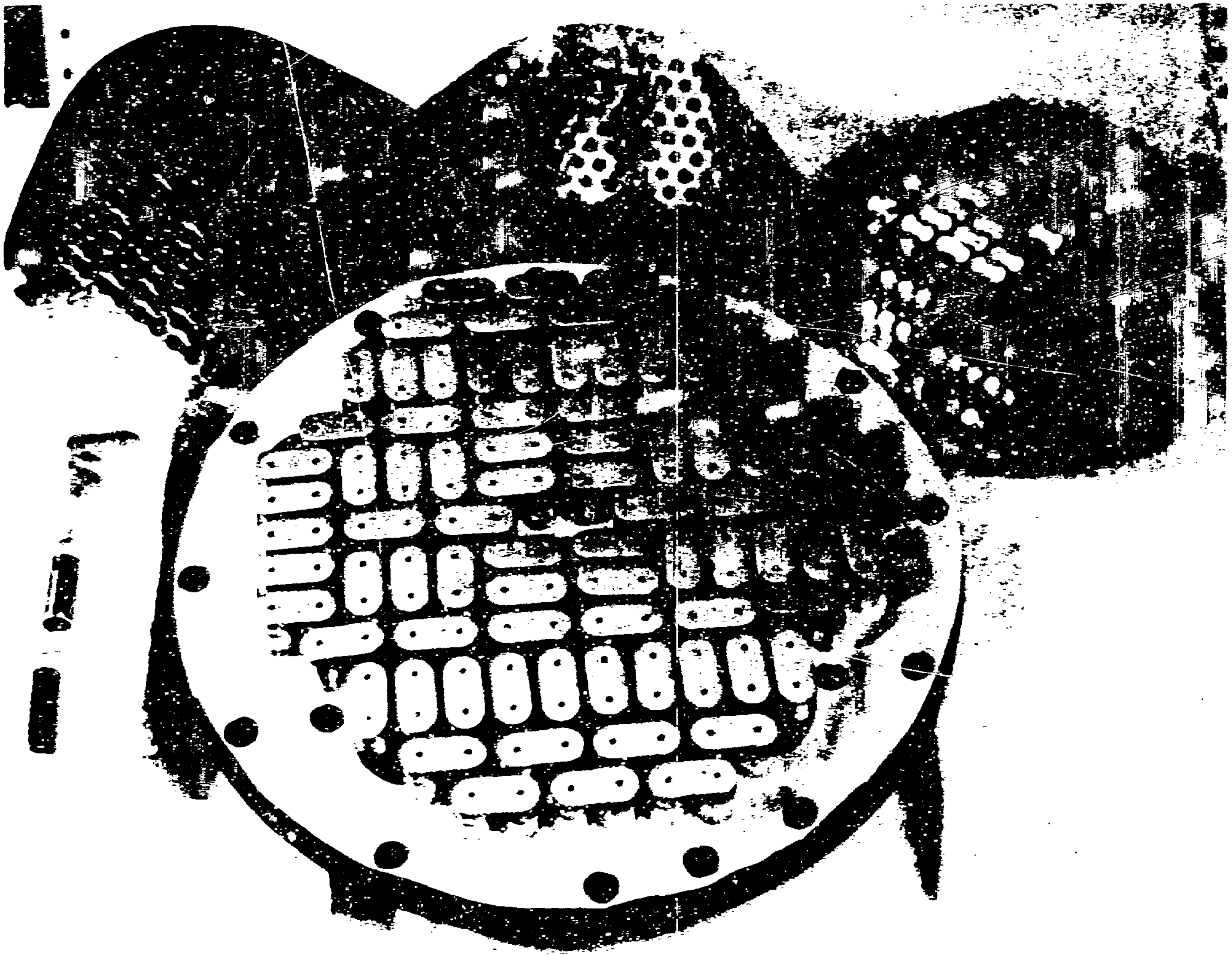

Figure 5-13. Typical Flat-Plate Thermoelectric Converter

input signal. Two crystals are required as a single crystal cannot generate waves with amplitudes suitable for fuel atomization, particularily at low temperatures. They are oriented such that the waves generated by the individual crystals constructively interfere with each other and produce a larger amplitude.

The generated waves travel along the length of the atomizer body, and are reflected internally. When the distance from one end of the body to the interface between the crystals is an odd multiple of the quarter-wavelength (that is, the wavelength is multiplied by 1/4, 3/4, 5/4, and so on), the generated waves are in phase with those reflected, resulting in a standing wave[50]. The greatest amplitude for them occurs at the antinodes and the atomizer body is designed to maximize this. It is constructed so that the largest amplitude is located at the atomizer exit. This is made possible by reducing the body diameter at this point, which amplifies the waves sufficiently for atomization to occur[52].

5.9.2.2. Description. A typical atomizer was shown in Figure 5-1, and additional details appear in Figure 5-14. The horn can be made from a number of materials, including titanium[52] and aluminium. The latter is preferred as it is lower in price and is easier to manufacture than the former, though it can experience greater losses of acoustic energy. The piezoelectric crystals can be made from $BaTiO_3$.

The electronic driver should be designed so that the atomizer will resonate at 60 kHz, which will atomize the fuels mentioned in par. 5.1.1. over the given temperature ranges and fuel flow rate of 1.0-5.0 lb/hr. The atomizer itself must be designed to withstand prolonged exposure to the temperatures of combustion.

As was mentioned in par. 5.6.3.1., ultrasonic atomizers have been successfully operated over the ambient temperature range of -40°F (-40°C) to +122°F (+50°C). This represents a difference of 162°F (90°C). The requirement for this application is that the atomizer operate from -65°F (-54°C) to +70°F (+21°C), with a temperature difference of 135°F (75°C).

Due to the smaller required ambient temperature range, an ultrasonic atomizer for the heater would be easier to operate. However, since the proven temperature limits are higher than those required for the heater, it will be necessary to design the driver circuitry to bias the atomizer operating characteristics to the lower temperatures.

Multifuel capability of the heater is a requirement, as given in par. 5.1.1. Over the aforementioned test temperature range, the atomizers were able to produce a mist suitable for smokeless combustion using a variety of fuels, with no deterioration in performance being noted.

5.9.3. Control System.

5.9.3.1. General. A block diagram showing the mechanical and electrical controls appears in Figure 5-15. The following is a description of the

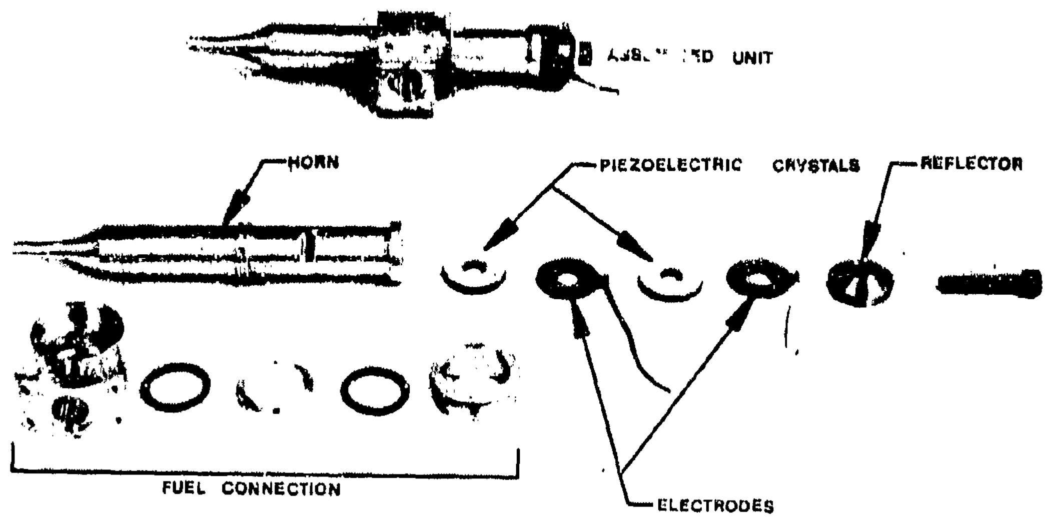

Figure 5-14. Ultrasonic Atomizer Assembly

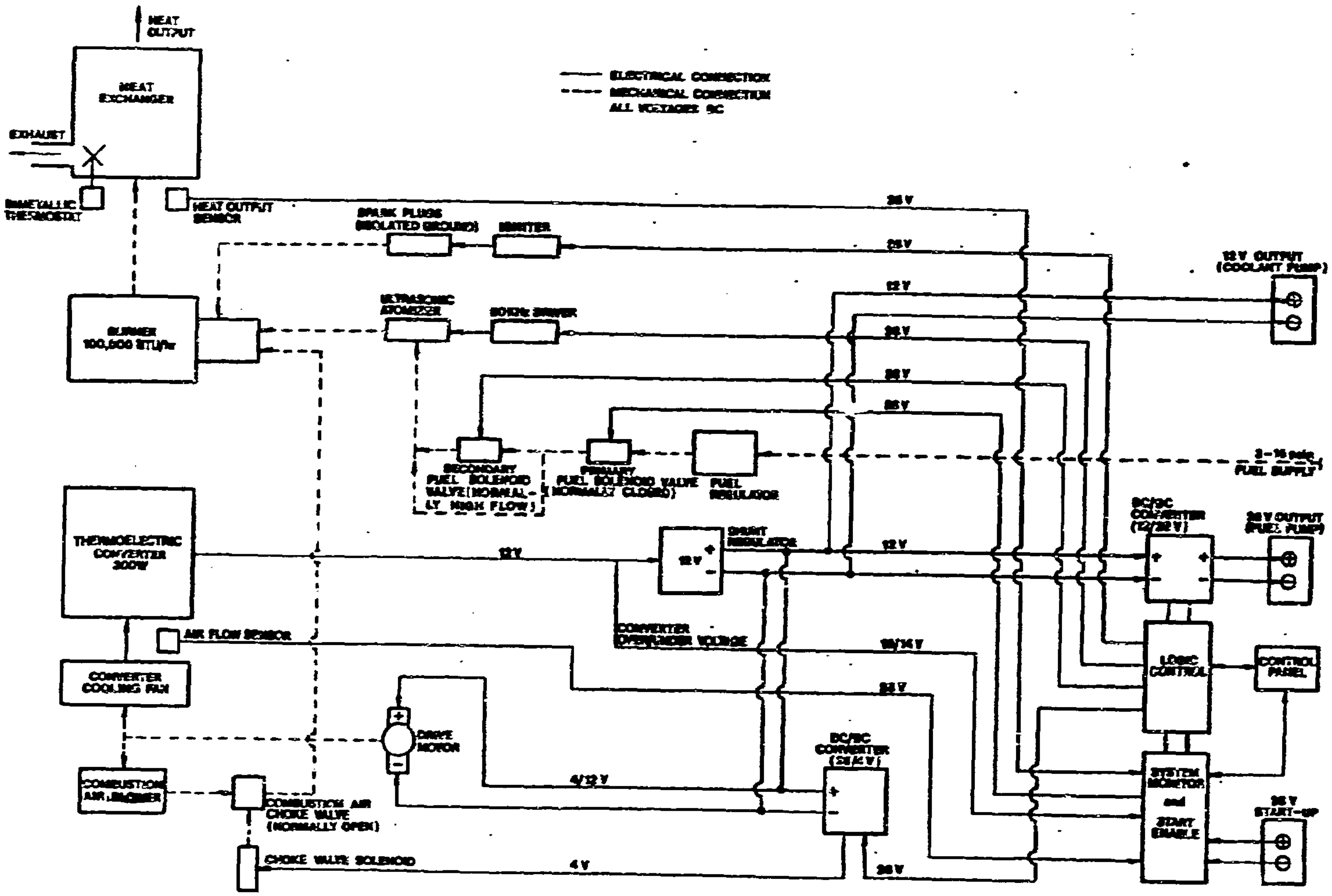

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FIGURE 5-15. CONTROL SYSTEM BLOCK DIAGRAM start-up procedure, concentrating on the electrical aspects. Table 5-10 summarizes the sequence.

5.9.3.2. Step 1 - heater off. This is the condition of the heater before a cold start. All the systems are shut off and the thermoelectric converter is not producing any power. The temperature is at or near cold ambient.

5.9.3.3. Step 2 - heater on, not started. Prior to start-up, a number of subsystems must be powered up and operating. When the heater switch is turned on, the external 28 VDC battery will activate the igniter, the ultrasonic fuel atomizer, 28 -> 4 VDC DC/DC voltage converter, the fan drive motor, the secondary fuel solenoid valve, and combustion air choke valve solenoid. Both the secondary fuel solenoid valve and the combustion air choke valve are in their restricted flow positions. When all subsystems have been cleared, the system can be started.

5.9.3.4. Step 3 - start-up. To start the system, the start button is pushed. When no alarms are present, the primary fuel solenoid valve and electrically-operated fuel pump (when used) are turned on, giving a fuel delivery rate of 1.0 lb/hr. The secondary fuel solenoid valve has two fuel flow settings - low (1.0 lb/hr) and high (5.0 lb/hr), maintaining the high setting when shut off. During this step, this valve is activated, giving the 1.0 lb/hr fuel flow. The fuel passes through the ultrasonic atomizer and is carried by the combustion air stream into the combustion chamber where it is ignited.

5.9.3.5. Step 4 - system powering up. While powering up, there are two points where the system changes automatically. The first one occurs when the TEC voltage exceeds 4 VDC. At this point the fan motor starts to draw its power from the TEC instead of the 28 -> 4 VDC DC-DC converter. As the TEC voltage builds, the fan motor will increase its speed.

5.9.3.6. Step 5 - system activation. The second instance where the system changes itself occurs when the TEC voltage reaches 8 VDC, as the heater becomes electrically self-sustaining. The following will then occur. The 12 -> 28 VDC DC-DC converter is activated, the external battery is disconnected, and the igniter is turned off. The secondary fuel solenoid valve opens up (allowing a fuel flow rate of 5.0 lb/hr), the 28 -> 4 VDC DC/DC voltage converter is deactivated, and the combustion air choke valve opens to allow full air flow.

5.9.3.7. Step 6 - heater fully operational. The TEC is producing its full power of 300 W at 12 VDC, and the maximum amount of heat is being delivered to the exchanger. Normal steady-state operation has been achieved.

5.9.3.8. Shutdown alarms. While the system is operating, there are three conditions that are being monitored which, if they change from normal setting, will cause the heater to shut down. These are circulating air flow, TEC overvoltage, and high circulating air temperature, and are displayed by indicator lights on the control panel. No audible alarms will be used. Once an alarm has been activated, the primary fuel solenoid valve

Table 5-10. Heater Operating Sequence

		Conditions and Steps									
		Step 1 System Cold Shut-Down	Step 2 System On	Step 3* System Start	Step 4 System Power Up	Step 5 System Total Activation	Step 6 System Running	Shut-Down Alarms	System Manual Shut-Down	Step 2A** Restart	Step 3A+ Restart
Thermoelectric Converter	- Status	Off	Off	On	On	On	On	On	On	On	On
	- Voltage	-	-	>0	>4	>8	12	X	X	4-8	4-8
System Switch Status		Off	On	On	On	On	On	On	Off	Off-On	On
Start Button Status		X	Off	On (Mom)	Off	X	X	X	X	Off	On (Mom)
Start Timer Status		Off	Off	On (1 Min)	X	Off	Off	X	X	Off	On (1 Min)
Converter Overvoltage Alarm Status		X	X	0	0	0	0	1++	X	X	X
Air Flow Sensor Alarm Status		X	X	0	0	0	0	1++	X	X	0
Overheat Alarm Status		X	X	0	0	0	0	1++	X	X	0
External Battery	- Status	Disconnected	Connected	Connected	Connected	Disconnected	Disconnected	X	Disconnected	Connected	Connected
	- Voltage	-	28	28	28	-	-	X	-	28	28 ->X
Fan Drive Motor Voltage		-	4	4	4 or VTEC	VTEC	12	VTEC	VTEC	VTEC	VTEC
Combustion Air Choke Valve Solenoid	- Status	Off	On	On	On	Off	Off	Off	Off	On	On
	- Voltage	-	4	4	4	-	-	-	-	4	4
Combustion Air Choke Valve Status		Open	Closed	Closed	Closed	Open	Open	Open	Open	Closed	Closed
Igniter	- Status	Off	On	On	On	Off	Off	Off	Off	On	On
	- Voltage	-	28	28	28	-	-	-	-	28	28
Ultrasonic Atomizer	- Status	Off	On	On	On	On	On	Off	Off	On	On
	- Voltage	-	28	28	28	28	28	-	-	28	28
Primary Fuel Solenoid Valve	- Status	Closed	Closed	Open	Open	Open	Open	Closed	Closed	Closed	Open
	- Voltage	-	-	28	28	28	28	-	-	-	28
Secondary Fuel Solenoid Valve	- Status	Off	On	On	On	Off	Off	On	On	On	On
	- Flow Setting	High	Low	Low	Low	High	High	Low	Low	Low	Low
	- Voltage	-	28	28	28	-	-	28	28	28	28
Shunt Regulator Status		Off	Off	Off	Off	Off	Active	X	X	Off	Off
28->4 DC/DC Converter	- Status	Off	On	On	On	Off	Off	Off	Off	On	On
	- Voltage In	-	28	28	28	-	-	-	-	28	28
	- Voltage Out	-	4	4	4	-	-	-	-	4	4
12->28 DC/DC Converter	- Status	Off	Off	Off	Off	On	On	X	X	Off	Off ->X
	- Voltage In	-	-	VTEC	VTEC	VTEC	12	VTEC	VTEC	VTEC	VTEC
	- Voltage Out	-	-	-	-	28	28	X	X	-	-
Coolant Pump	- Status	Off	Off	On	On	On	On	On	On	On	On
	- Voltage	-	-	VTEC	VTEC	VTEC	12	VTEC	VTEC	VTEC	VTEC
Fuel Pump	- Status	Off	On	On	On	On	On	X	X	On	On
	- Voltage	-	28	28	28	28	28			28	28
Fuel Flow (lb/hr)		-	-	1.8	1.8	5.8	5.8	-	-	-	1.8
Time Duration		X	X	TBD	TBD	TBD	X	10 Sec	TBD	X	1 Min

* Heater will not start with an alarm condition
** Heater will not restart with generated voltage over 8 VDC
\+ After 1 minute, system will join present condition Step
\++ Any combination of these alarms will cause heater shut-down

All voltages VDC nominal

LEGEND:

VTEC = Thermoelectric converter output voltage
X = "Does not matter"
0 = Non-alarm condition
1 = Alarm condition
\- = Nil
TBD = To be determined

is shut off and the heater allowed to cool down. The subsystems will remain operational as long as sufficient power is available from the thermoelectric converter, including the combustion air blower, which will purge the burner with fresh ambient air.

5.9.3.9. System manual shutdown. The heater is shut down by turning off the system switch. This totally disables the external battery, and shuts off the primary fuel solenoid valve, the igniter (if operating), the electrically operated fuel pump (if used), and the ultrasonic atomizer. The combustion and circulating air subsystem will remain active as long as the TEC is producing sufficient power. This subsystem will aid in the cooling of the unit while the burner is being purged.

5.9.3.10. Step 2A - warm restart preliminary. The heater may need to be restarted while warm and the TEC is producing power. If the voltage of the TEC is below 8 VDC, the restart can occur. What occurs is similar to that described in par. 5.9.3.3., with the exception that if the heater switch remained on, it must first be turned off and then on in order to enable the start sequence and clear the alarm circuits.

5.9.3.11. Step 3A - warm start. This step is similar to that described in par. 5.9.3.4., except there is a minimum time limit in which this condition must be maintained, regardless of the TEC output voltage. This is to allow the burner to start up properly. After this time passes, the heater will return to its normal start-up sequence specified by the TEC voltage.

5.9.4. Liquid Multifuel Burner. The burner layout is shown in Figure 5-16.

Combustion air and atomized fuel enter the combustion chamber through the inlet and are partially mixed. This mixture is ignited and, due to the momentum of the flow, swirls about the walls of the chamber, heating the thermoelectric converter. Mixing continues due to the flow turbulence. The swirling also causes the mixture to move towards the outlet into the heat exchanger.

Each heat exchanger - personnel, coolant, and portable - has its own burner. This is favourable because the integration of the burner and heat exchanger eliminates the difficulty of making high temperature leak tight connections. The only connection necessary to seal the exhaust path is between the thermoelectric converter and the burner.

Included in Figure 5-16 is a detail of the burner sealing arrangement. Between the combustion chamber and the burner is a high-temperature seal, such as a braided ceramic fibre. Prior to attaching the HPM to the exchanger to be used, the seal is loosely put in place in the combustion chamber by hand. When the two sections are put together, they will be held together by a quick-release V-band clamp (see par. 5.9.7. for additional details). Sufficient force will be exerted by the clamp to deform the sealing material, making the joint leak-proof.

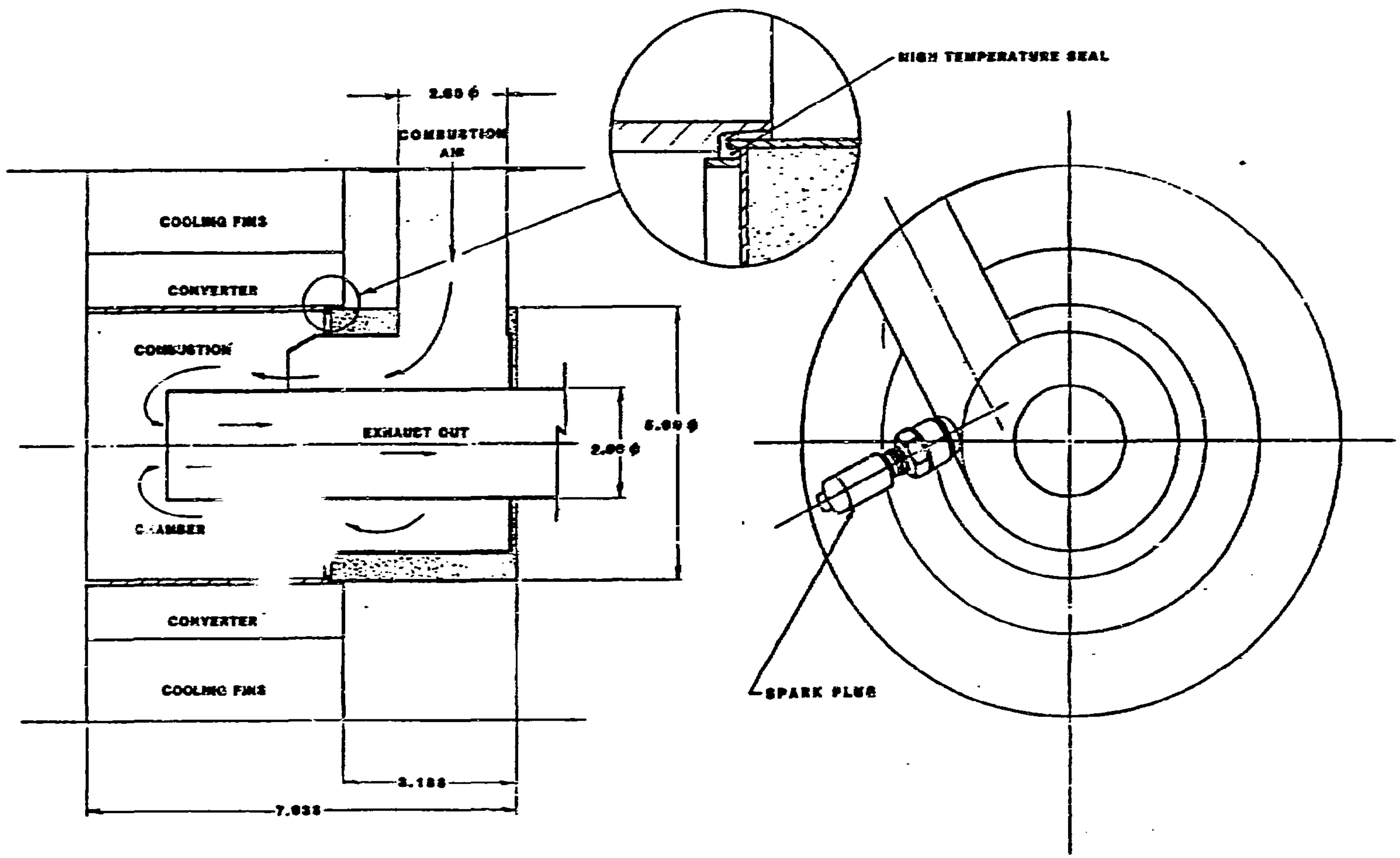

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FIGURE 5-16. LIQUID MULTIFUEL BURNER

The decision to integrate the burner with the heat exchanger was also analyzed from a cost standpoint. The cost of a burner is estimated to be equivalent to the cost of a high-temperature, leak-tight connection. The major components of the burner subsystem — atomizer, ignition circuit, fuel delivery and air delivery — are part of the HPM. The burner itself is only a mixing and combustion chamber fabricated from a high temperature, corrosion resistant metal such as Hastelloy "X". Also this exchanger-burner integration saves valuable space and weight, while increasing maintainability.

5.9.5. Fuel Control System. The fuel control system for the heater is required to deliver a constant flow of fuel during steady-state operation and a reduced amount of fuel and combustion air for start-up. To keep the steady-state fuel flow rate constant at 5.0 lb/hr, the control system must compensate for fuel viscosity variations due to changes in both ambient air temperature and fuel type. During start-up, the fuel control system will reduce the fuel flow rate to 1.0 lb/hr with stoichiometric, or less, air. This is because full fuel and air delivery during cold start tends to quench or blowout the initial combustion phase. This control feature will ensure ignition and still allow the HPM to come up to power quickly.

The fuel control system is shown schematically in Figure 5-17. Additional details are available in Figure 5-15. It consists of a quick release connection with its inlet situated on the heater's outer shell, a pressure regulating valve, a temperature-actuated needle valve, a primary fuel solenoid valve (normally closed), a secondary fuel solenoid valve for start-up flow (1.0 lb/hr) or steady state flow (5.0 lb/hr), and an ultrasonic atomizer. There is also a rotary solenoid-actuated choke valve in the combustion air delivery duct. The fuel is delivered to the system at 3 to 15 psig from an electrically-operated fuel pump. For portable use, a manually pressurized fuel tank is used which will allow one hour of operation before refueling is required. In either mode of operation, the pressure regulating valve will provide a fuel supply of constant pressure to the temperature-actuated needle valve. Power for start-up is obtained from an external 28 VDC battery until the HPM is electrically self-sustaining.

At start-up, the drive motor for the combustion air blower will be operated at 4 VDC, which will be taken from the 28 -> 4 VDC DC/DC voltage converter. When the TEC voltage rises above 4 VDC, the drive motor will take its power directly from the TEC output. The anticipated behaviour of the TEC during start-up is shown in Figure 5-18. The TEC voltage is expected to reach the steady-state value of 12 VDC in approximately 3 minutes after ignition. The reduced fuel flow rate required for start-up will be obtained when the primary fuel solenoid valve is open and the secondary fuel solenoid valve energized to allow 1.0 lb/hr of fuel to pass through the fuel delivery subsystem (see Figure 5-15). The reduced combustion air flow rate of 3 SCFM for start-up will be achieved by the operation of the fan drive motor at 4 VDC and by the activation of the combustion air choke valve. As the TEC voltage rises, the blower discharge flow rate will increase. When the TEC voltage reaches 8 VDC, both the secondary fuel solenoid valve and the combustion air choke valve will open. The fuel flow will then increase to

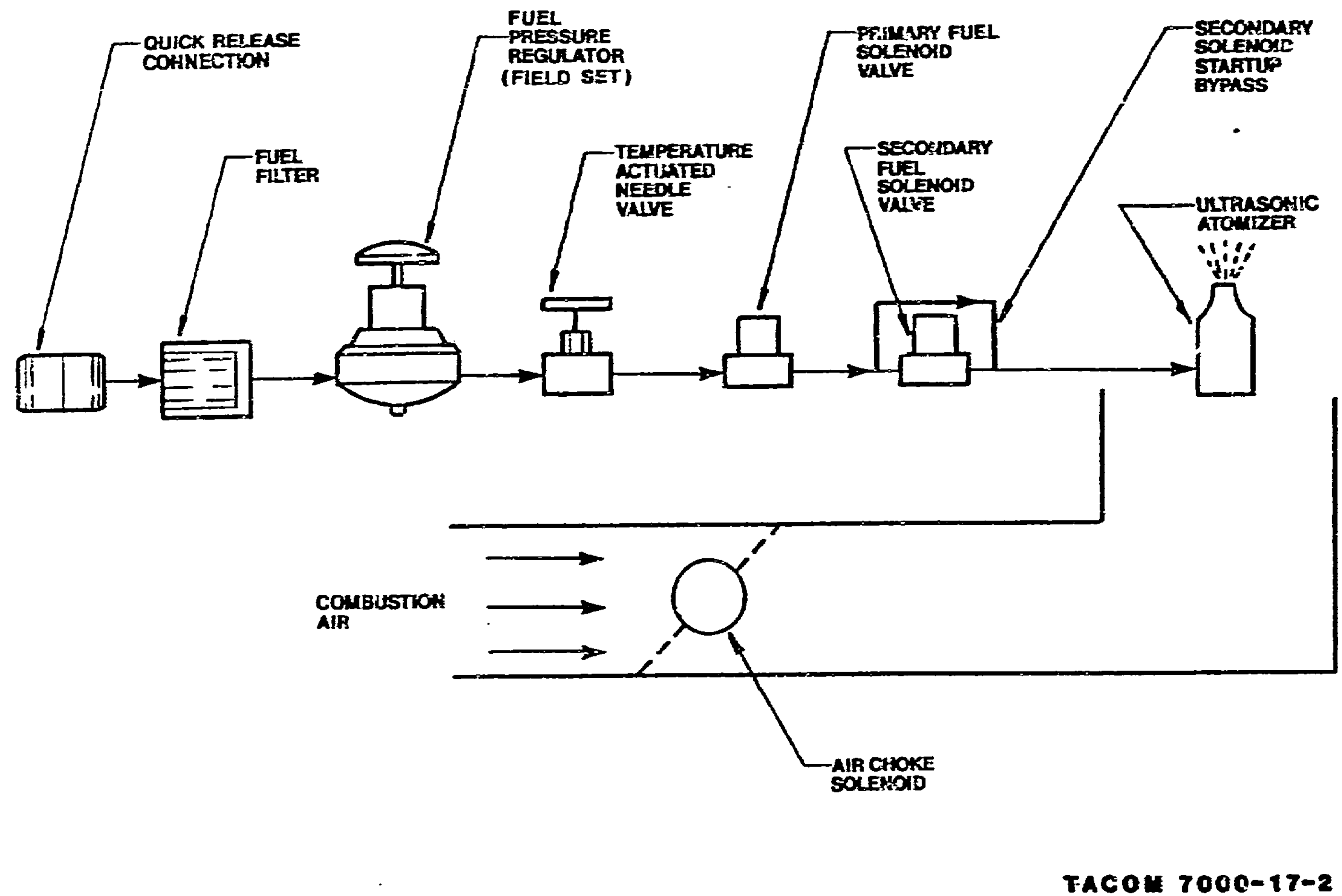
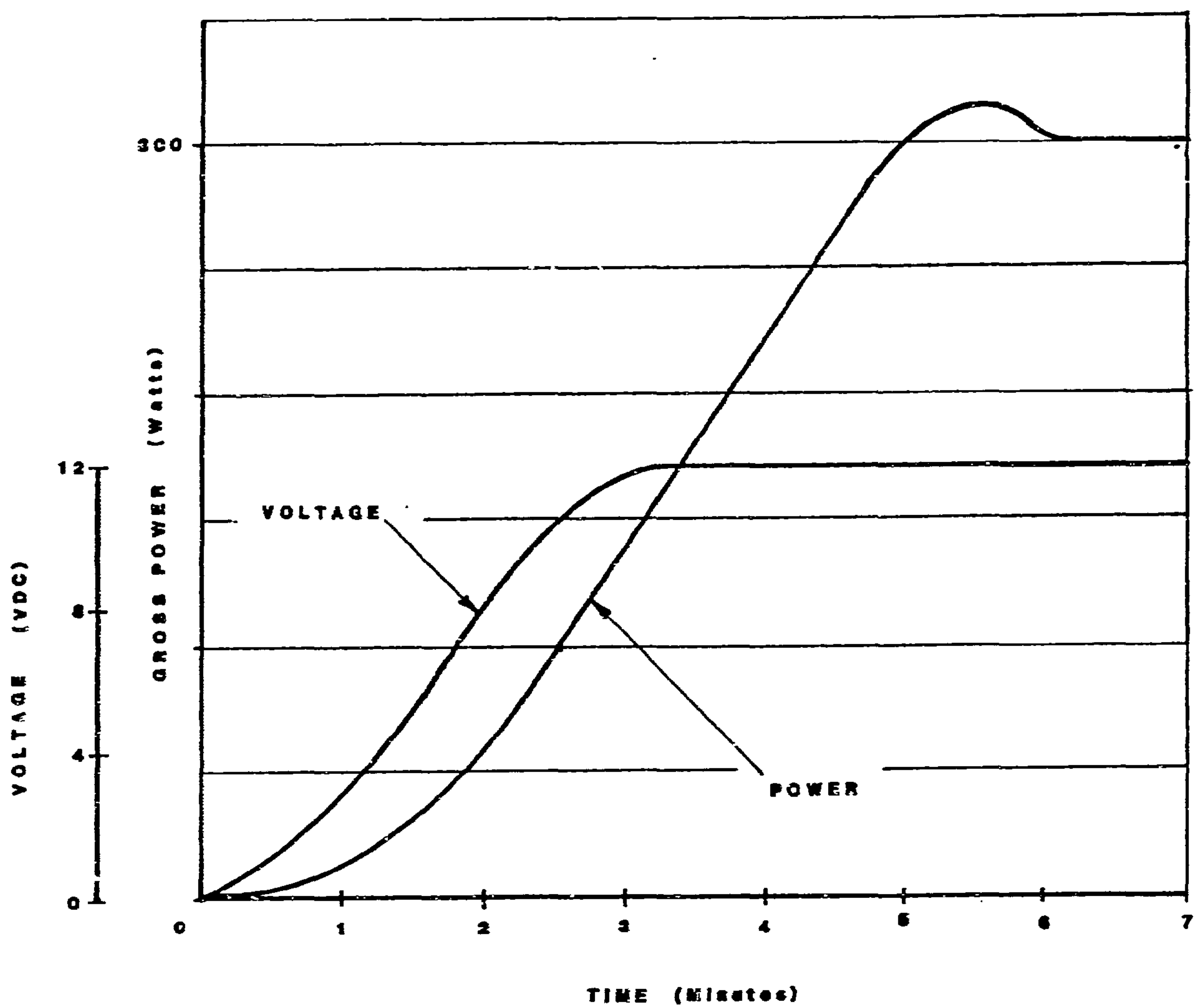


FIGURE 5-17. FUEL CONTROL SYSTEM



TACOM 7000-18-1

FIGURE 5-18. ANTICIPATED THERMOELECTRIC CONVERTER STARTUP CHARACTERISTICS the steady-state value of 5 lbs/hr, as shown in Figure 5-19, and the air flow will increase to about 45 SCFM, as shown in Figure 5-20. Combining Figures 5-19 and 5-20 yields a plot of the percentage of excess combustion air during start-up as shown in Figure 5-21. As expected, a sudden increase in excess air occurs at a TEC voltage of 8 VDC. When the steady-state voltage of 12 VDC is reached, the percent excess combustion air is at its steady-state value of 250%.

The viscosity of a specific fuel varies dramatically within its useful temperature range. For example, the viscosity of DF-2, with a temperature change from +70°F down to 0°F, increases by a factor of about 5[53,54]. If no compensation in the fuel delivery system were provided to counter this viscosity change, the amount of fuel delivered at 0°F would be substantially less than delivered at 70°F. For satisfactory operation of the HPM over the required temperature range of -65°F to +70°F, the fuel delivery system must compensate for viscosity changes due to temperature variations. Such compensation will be accomplished with a temperature-actuated needle valve, which will consist of a needle valve with a bimetallic coil attached to its stem. The coil and the stem will have a protective cover to ensure cleanliness and to prevent seizing. The action of the coil will be such that the flow restriction is reduced as the temperature decreases, effectively reducing the head loss for the colder, more viscous fuel. The effect will be to keep the flow rate of fuel constant in spite of temperature changes. In order to provide sufficient compensation, the bimetallic coil will be required to rotate 180° as its temperature changes from -65°F to +70°F. The valve will be situated directly behind the air circulation fan and control will be based upon the inlet air temperature. The fuel delivered to the heater is controlled by the ambient air temperature. This type of control suits all applications since less heating is required at higher ambient temperature for all three heaters.

Another option that was considered was electronically monitoring the fuel temperature and signalling an electrically-actuated control valve. Such an electromechanical control system would have provided good compensation characteristics but the cost would have been higher, the system complexity would have increased, and electric power would have been required. The method using the bimetallic actuator was adopted due to its simplicity and lower cost. Although some initial development work may be necessary, all of the components for the control valve will be available commercially.

Fuel viscosity will also vary when there is a change of fuel type. For example, when changing from DF-2 to DF-1 at 0°F the viscosity is reduced by a factor of about 2[53,54]. The less viscous DF-1 would flow easier through the fuel delivery system resulting in excess fuel being delivered to the ultrasonic atomizer. Viscosity change compensation is necessary for the different fuel types and it was judged that manual actuation would be adequate. One reason for this is that viscosity changes due to varying fuel types are less pronounced than changes due to temperature variations. Compensation will be accomplished by adjusting the pressure regulator output pressure for the various fuels. A less viscous fuel will require a lower regulator output pressure in order to maintain a constant flow rate. A dial

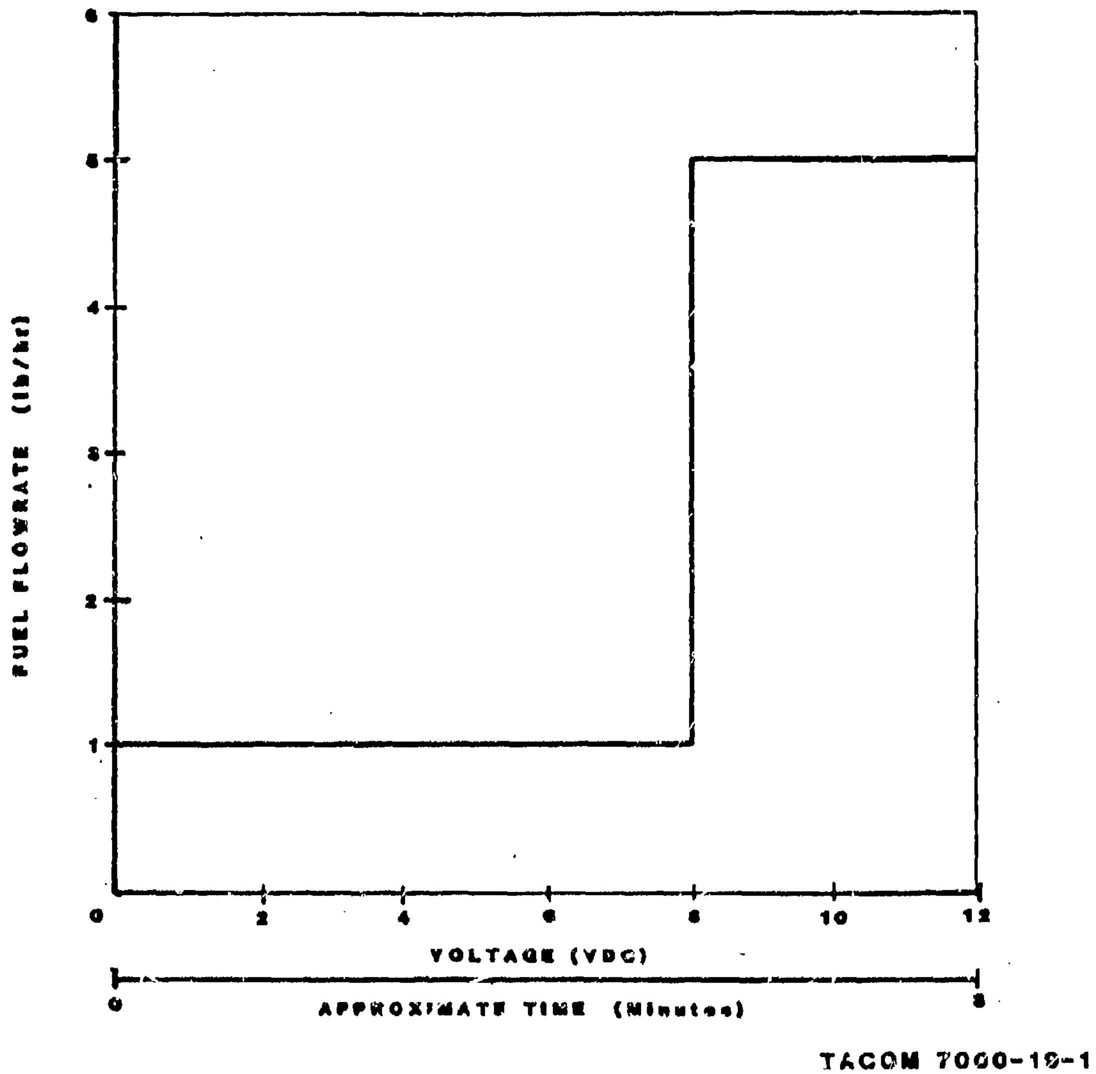
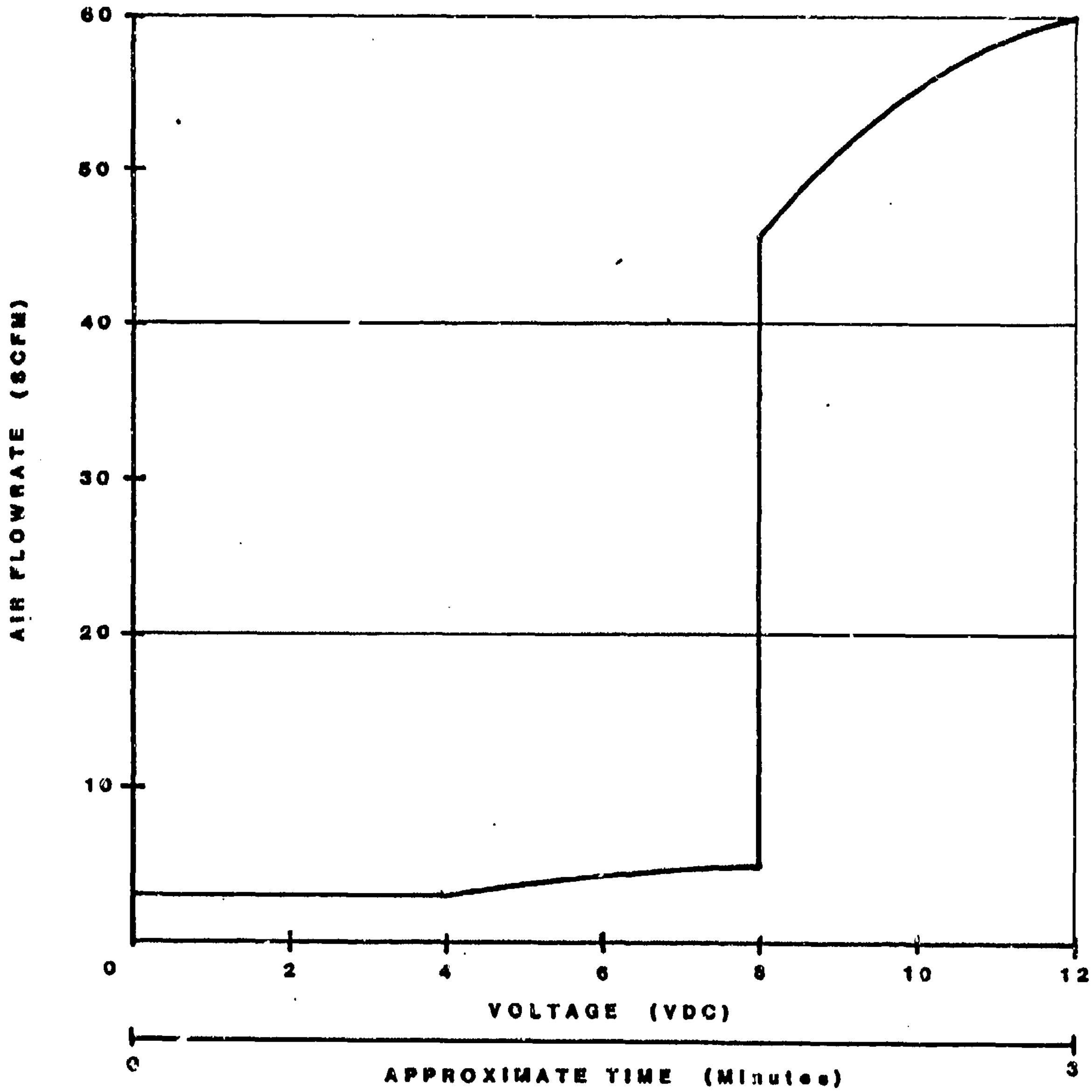
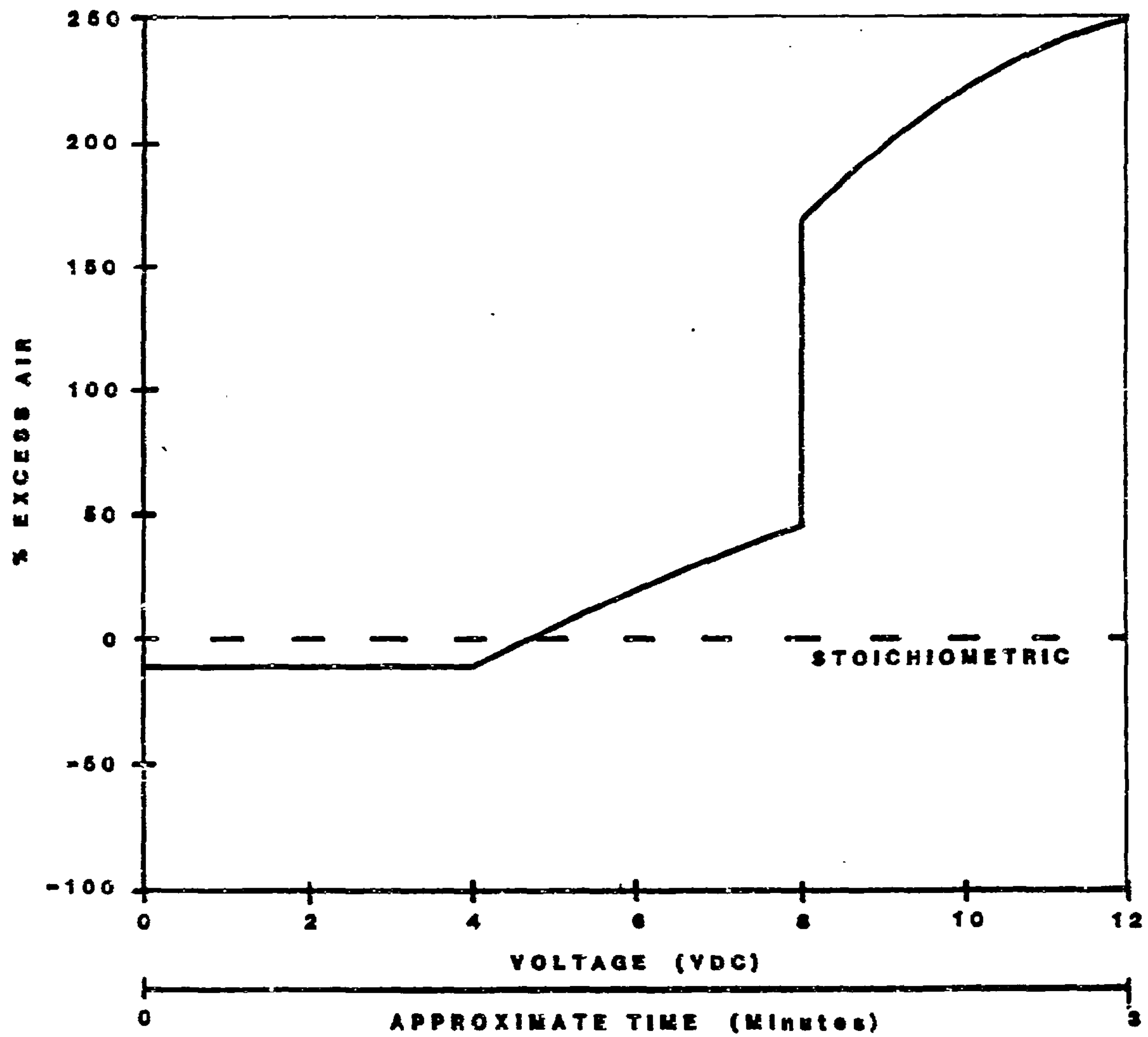


FIGURE 5-19. FUEL FLOW DURING STARTUP



TACOM 7000-20-1

FIGURE 5-20. COMBUSTION AIR FLOW DURING STARTUP



TACOM 7000-21-1

FIGURE 5-21. EXCESS COMBUSTION AIR DURING STARTUP on the stem of the pressure regulating valve will have predetermined settings for the different fuels.

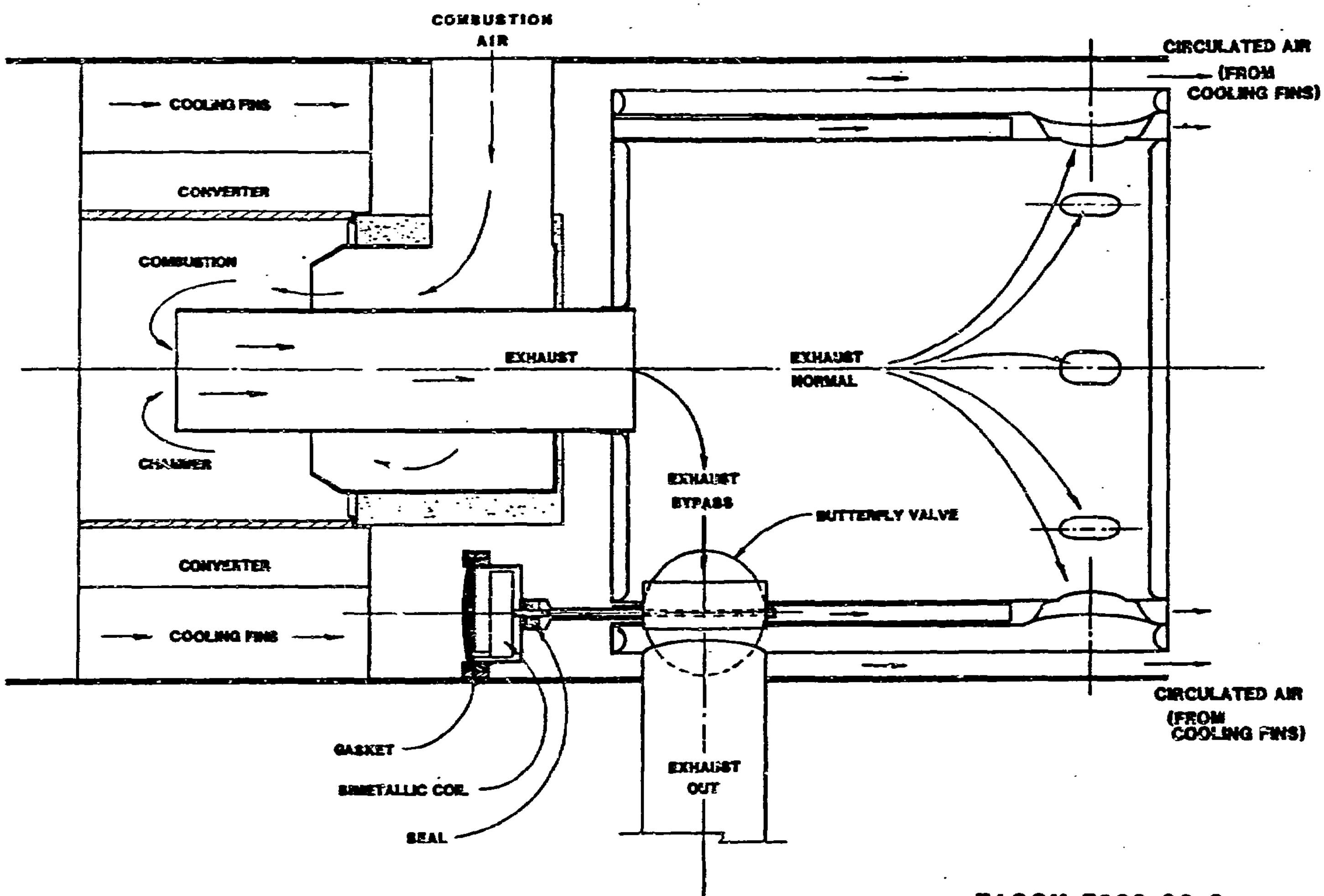
In mass production, the fuel control system will be a relatively inexpensive portion of the HPM (see par. 5.12.). Satisfactory fuel delivery control will be obtained without the requirement for electrical power. The system will provide quick and reliable starts, and the approach to maintain simplicity should result in a reliable, low-maintenance fuel control system.

5.9.6. Thermal Output Control. The rate of heat delivery by the personnel and coolant heat exchangers will be controlled by a thermostatically-actuated bypass valve. The butterfly type valve will be located in the heat exchanger directly above the exhaust outlet pipe, which will allow varying quantities of the hot combustion gases to bypass it. Figure 5-22 shows a conceptual sketch of the heat control system for the personnel heat exchanger.

The thermostatic actuator will be a bimetallic coil situated between the exchanger and the thermoelectric converter and is connected to the bypass valve by a sheathed actuator rod. For the personnel heat exchanger, the bimetallic coil will sense the temperature of the air which has passed over the converter cooling fins, which is the air circulating within the personnel compartment. During normal operation, the temperature difference between the circulating air and that of the personnel compartment will be constant. The sensing element will be biased to account for this temperature difference. As the temperature of the personnel compartment air increases, so will that of the circulating air, finally leading to an increase in the bimetallic coil temperature. The coil will expand as it warms, causing a rotation of the actuator rod, and opening the bypass valve an incremental amount. The set point temperature can be adjusted by loosening the front cover on the coil's casing and rotating it. This front cover will have a gasket to prevent any combustion gases from entering the circulating air.

The heat control for the coolant heat exchanger will be identical to that of the personnel heat exchanger except that the temperature sensed by the bimetallic coil will be that of the coolant. The coil casing will have a water jacket covering a portion of its surface, and the entire assembly will be insulated. A small flow of liquid will be tapped from the main coolant piping and will flow through this water jacket.

The major requirements for the bimetallic coil for the personnel heat exchanger are to overcome any developed torque and to affect 75° of rotation with a change of ambient temperature from 30°F to 70°F. The torque that will have to be overcome is estimated to be negligible. However, the torque was estimated for the worst conceivable case, which would occur if the entire exhaust flow impinged on only one half of the butterfly valve. The torque developed in this situation is calculated to be 0.26 in.-lb. It is estimated that the operating temperature of the coil due to conduction along the shaft from the valve to the coil would be 80°F above ambient. A similar



TACOM 7000-22-3

FIGURE 5-22. BURNER EXHAUST BY-PASS CONTROL (PERSONNEL HEAT EXCHANGER) temperature difference and torque are estimated for the coil for the coolant heat exchanger.

The amount of control that will be obtained is estimated to correspond to a bypass capability of 85%. Thus for the personnel heater, the heat output will vary between a maximum of 60,000 BTU/hr and a minimum of 19,000 BTU/hr (including 11,000 BTU/hr from the TEC). For the coolant heat exchanger, the heat output will be a maximum of 30,000 BTU/hr and a minimum of about 4,500 BTU/hr.

5.9.7. Personnel Heat Exchanger. The layout of the personnel heat exchanger is shown in Figure 5-23.

Exhaust gases from the combustion chamber enter the heat exchanger mantle and pass into an outer jacket prior to being vented into the outlet. Heat is transferred to the air circulated through the TEC cooling fins from the mantle's outer surface and from both air side surfaces of the jacket. A set of "U"-fins on the outside of the mantle are included to enhance the heat transfer. Air circulated through the thermoelectric converter cooling fins passes through the annuli formed by the mantle and jacket, and the jacket and exchanger outer shell and is exhausted into the personnel compartment. The exchanger will be attached to the remainder of the heater by means of a hinged quick-release V-band clamp (see Figure 5-32).

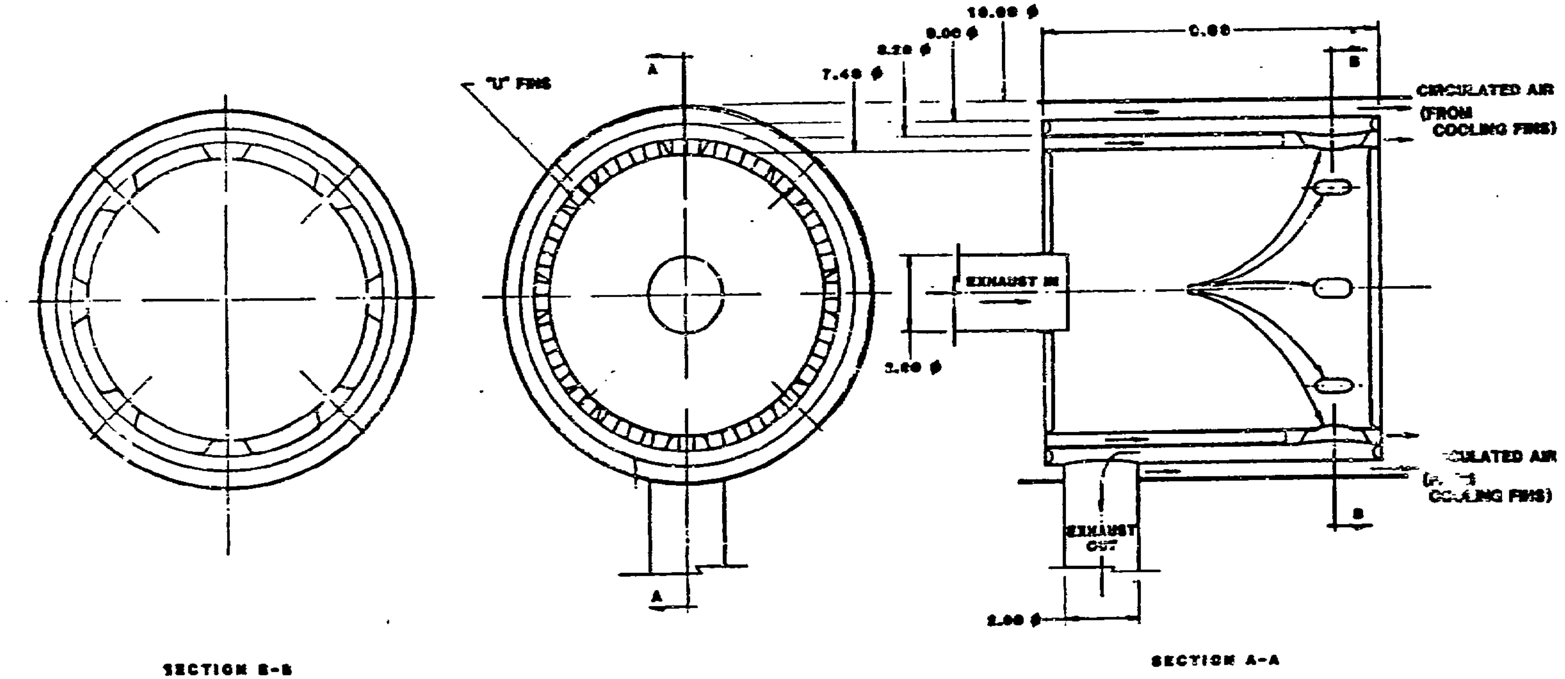
One such clamp around the the circumference of the heater's outer shell will be used. This will allow the outer shell of the HPM to be constructed as a complete unit since no access to the burner seal will be required. This will be possible as this seal will be leak-tight, preventing contamination of the circulating air by exhaust gases. See par. 5.9.4. for further details.

The clamp will be designed so that it will exert sufficient force on the joint between the HPM outer shell and that of the heat exchanger to prevent any shifting between the two sections. It will be hinged to permit easy removal and a quick-release latch will eliminate the need for special tools.

5.9.8. Coolant Heat Exchanger. The layout of the coolant heat exchanger is shown in Figure 5-24.

Exhaust gases from the combustion chamber enter the coolant heat exchanger and are circulated into an outer jacket prior to being vented into the outlet. Heat is transferred to the coolant from the mantle outer surface and from the coolant side surface of the jacket. A set of "U"-fins on the mantle exterior are included to enhance the heat transfer. The coolant passes through the annulus formed by the mantle and jacket. The exchanger will be attached to the remainder of the heater by means of a hinged quick-release V-band clamp.

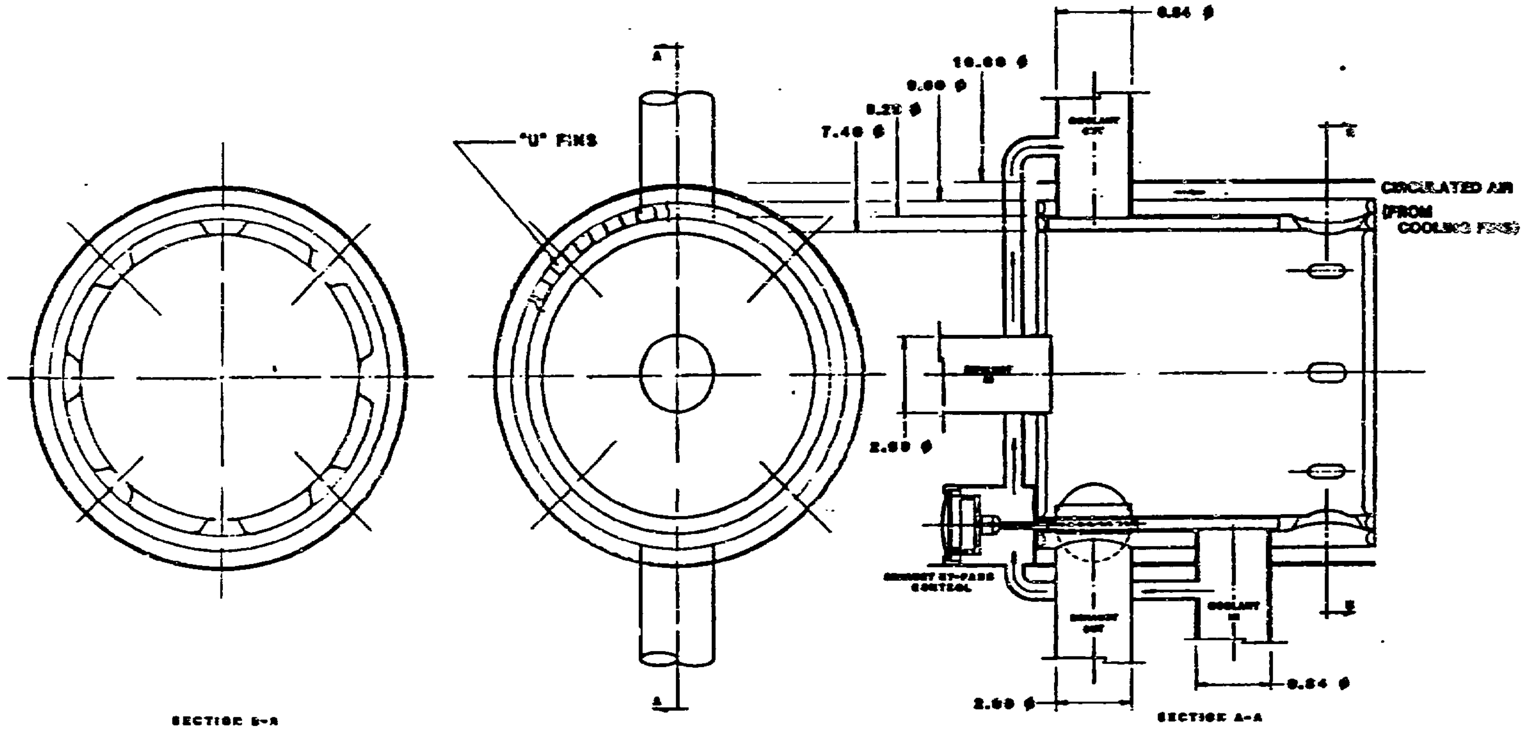
Details of the V-band clamping arrangement are identical to those for the personnel heat exchanger (see Figure 5-32).



NOTE: EXHAUST BY-PASS CONTROL NOT SHOWN

TACOM 7000-23-3

FIGURE 5-23. PERSONNEL HEAT EXCHANGER



TACOM 7000-24-3

FIGURE 5-24. COOLANT HEAT EXCHANGER

The coolant circulation pump shall be an electrically-driven gear pump, operating at 12 VDC and delivering approximately 90 USGPH at 10 psig minimum. It shall take its power directly from the thermoelectric converter output (see Figure 5-15) and shall operate continuously while the coolant preheater is functioning. Its power consumption is estimated to be 50 W.

A number of types of pumps are commercially available, such as gear, plunger, diaphragm, screw, rotary piston, and centrifugal. Of those examined, the gear pump was the best suited for several reasons. It was the smallest in size, with the other types being considerably larger. It was designed to withstand the coolant temperature, while others, the diaphragm pump in particular, were not suitable. Several units did not have the required combination of discharge flow rate and pressure. Figure 5-25 shows a gear pump performance curve based on manufacturer data[55]. A gear pump is self-priming which will allow it to be operated in any position while orientation will affect several of the other units. These factors combined made the gear pump unit best suited for this application.

5.9.9. Portable Heat Exchanger. The layout of the portable heat exchanger is shown in Figure 5-26.

The exhaust gases are mixed with the circulating air to provide the heat, assuming total recovery. It will be attached to the remainder of the heater by means of a hinged quick-release V-band clamp.

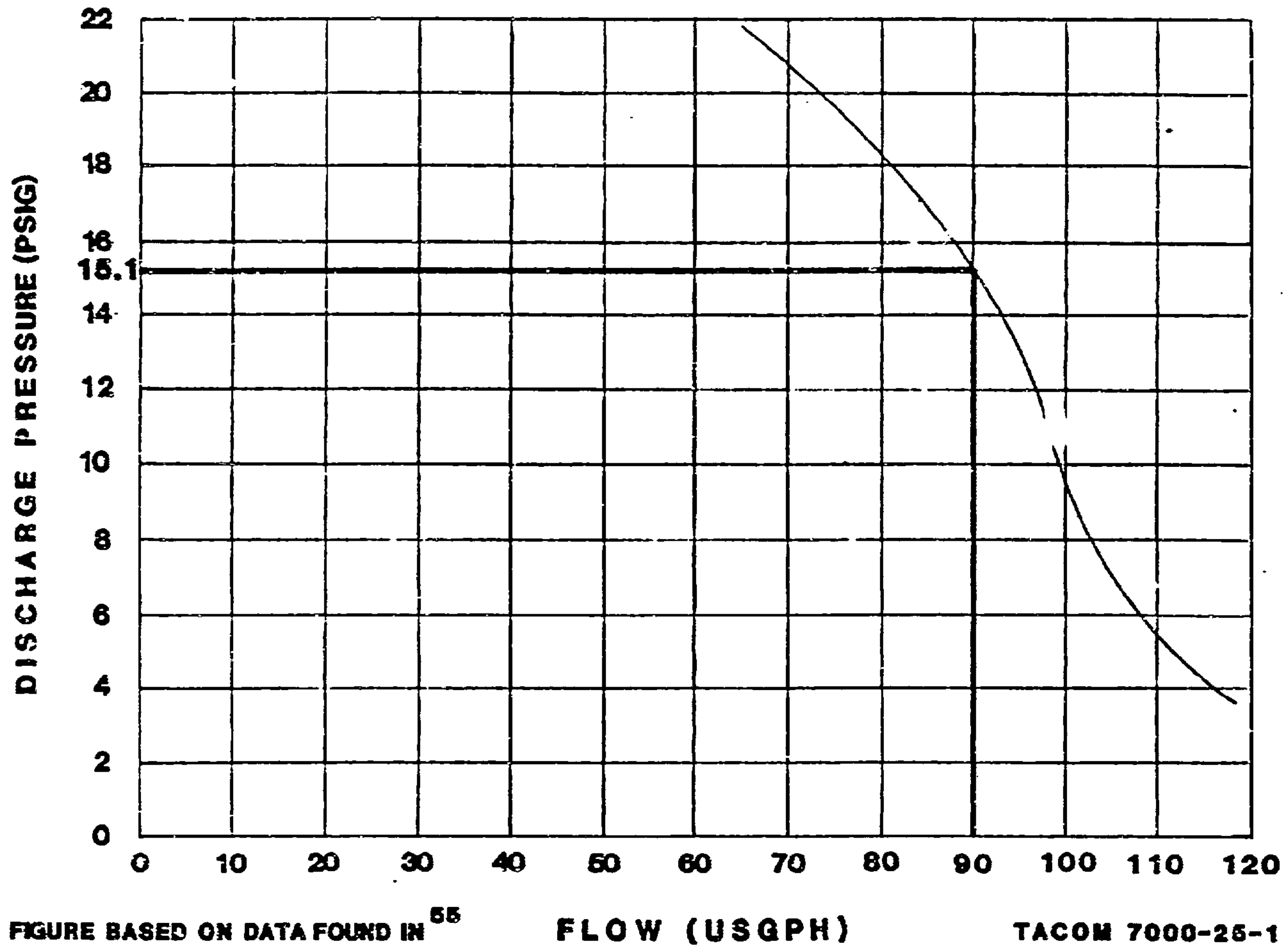
5.9.10. Combustion Air Blower and Air Circulation Fan. The personnel heater is required to have the capability to operate within an NBC environment. That is, the combustion air source must be independent of that for the circulating air.

Two possibilities exist: two fans driven by separate motors (operated by the control system either independently or simultaneously) or two fans driven by the same motor. The former mode would require a larger control system and would occupy a greater volume than would the latter. Consequently, the latter mode was selected.

The fan configuration to be used is shown in Figure 5-27. The design is based on information found in [56,57,58]. The combustion blower will be a centrifugal unit and the air circulation fan an axial, and both will be driven by a motor designed to operate between 4 VDC and 12 VDC.

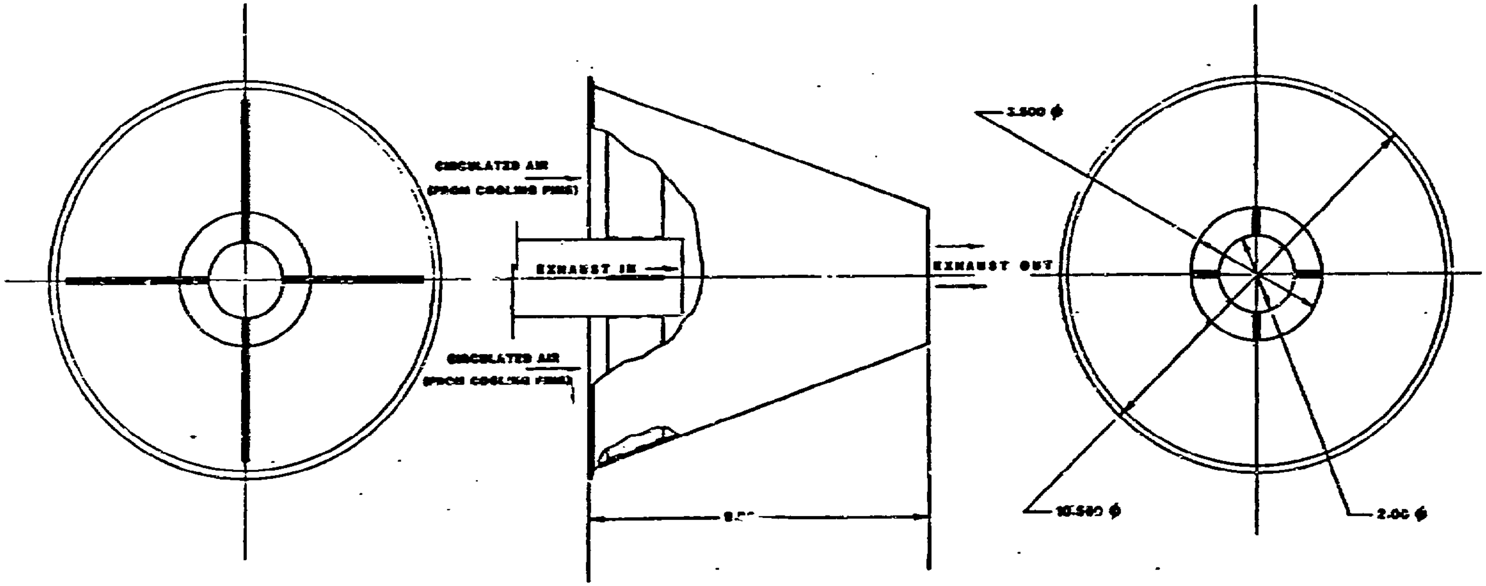
The combustion blower will be required to deliver an estimated 56-60 SCFM at about 1.8 in. water to the burner and heat exchangers for all heaters.

For the personnel heater, the air circulation fan will be required to deliver to the personnel compartment 190 SCFM of air at 1.3 in. water. It is estimated that the air circulation fan discharge pressure will be 2.4 in. water. Experience with radial fans in similar applications and flow systems indicates that less than 0.5 in. will be lost due to friction through the TEC cooling fins and the exchanger.



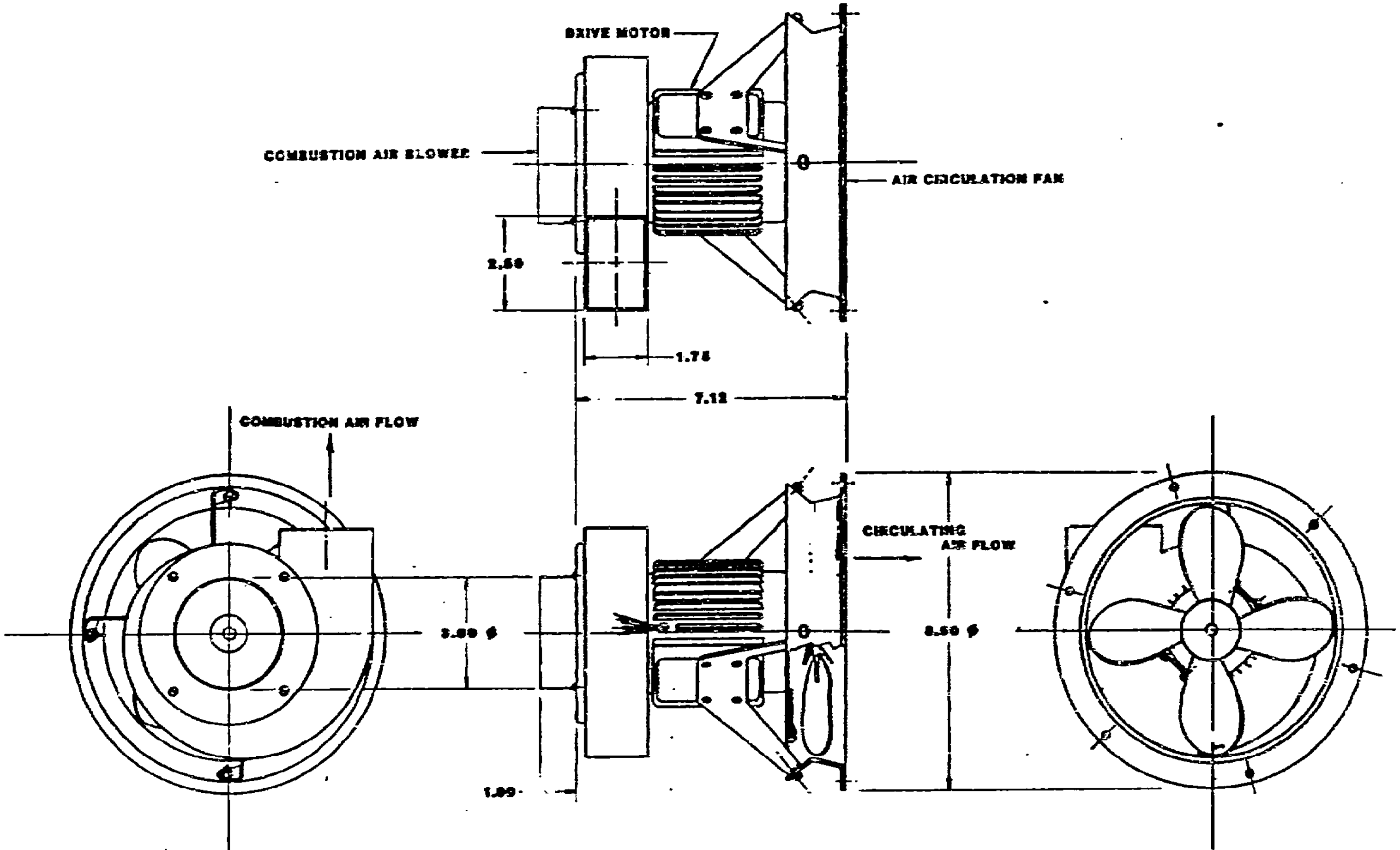
NOTE: FIGURE BASED ON DATA FOUND IN [55] TACOM 7000-25-1

FIGURE 5-25. COOLANT CIRCULATION PUMP PERFORMANCE



TACOM 7000-26-3

FIGURE 5-26. PORTABLE HEAT EXCHANGER



NOTE: FIGURE BASED ON [56,57,58]

TACOM 7000-27-3

FIGURE 5-27. COMBUSTION AIR BLOWER AND AIR CIRCULATION FAN

For the coolant heater, the circulated air, once it passes through the TEC cooling fins, will be discharged directly to atmosphere through the annulus formed by the heat exchanger shell and outer most surface of the coolant jacket (see Figure 5.24). It will not be required for heat exchanger operation.

For the portable heater, the air from the TEC cooling fins and the exhaust from the burner will be combined to deliver a required 180-200 SCFM at 0.75 in. water.

The fans were selected on the basis of what is known as the specific speed[59], which relates air delivery and static pressure, and is given by:

$$n_s = \frac{nQ^{1/2}}{P^{3/4}},$$

where:

n_s = specific speed (dimensionless),
n = fan speed (RPM),
Q = flow rate (SCFM),
P = static pressure (in. water).

If the motor operates at 5,500 RPM (which is approximately the anticipated speed), the combustion air blower would have a specific speed of 22,095, for which a centrifugal unit would be best suited (see Figure 5-28, which is based on data found in [59]). The TEC cooling fan would have a specific speed of 48,785, which would place it at the lower range of the axial fans, but in the range of the centrifugal units. However, due to size considerations, an axial fan would be preferred.

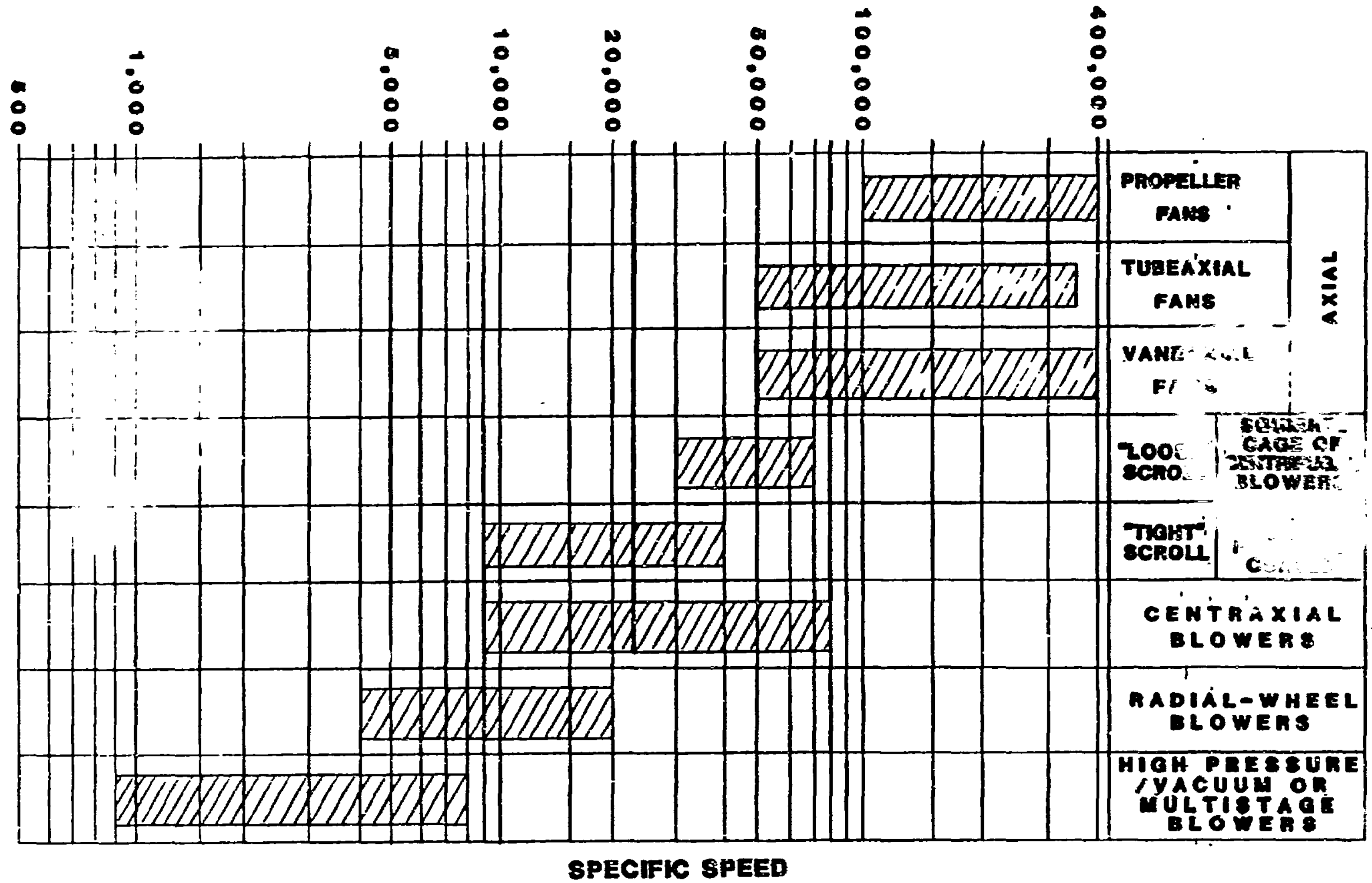
Figures 5-29 and 5-30 show performance curves for the combustion air blower and the air circulation fan, respectively. It should be noted that they are estimates based on information found in [60,61] and extrapolated to the anticipated operating conditions. They do not represent measured performance data for the fans which will be used for the HPM.

The electrical power required to operate the entire unit can be estimated as follows. The air horsepower (AHP)[59] for a fan is given by:

$$AHP = \frac{Q\ \Delta P}{6350},$$

where:

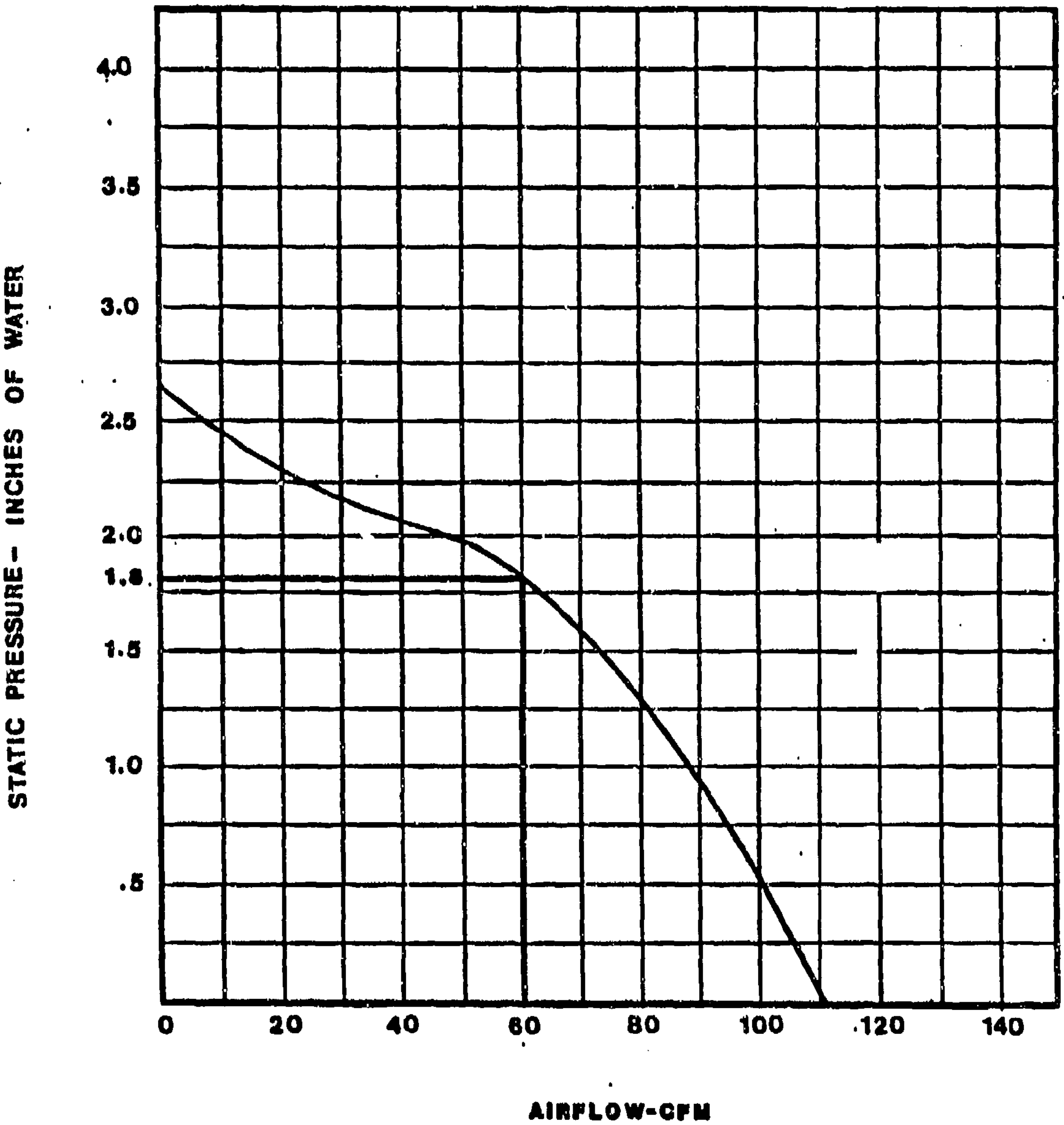
Q = flow (cfm),
ΔP = pressure drop (in. H_2O).



NOTE: FIGURE BASED ON DATA FOUND IN [59]

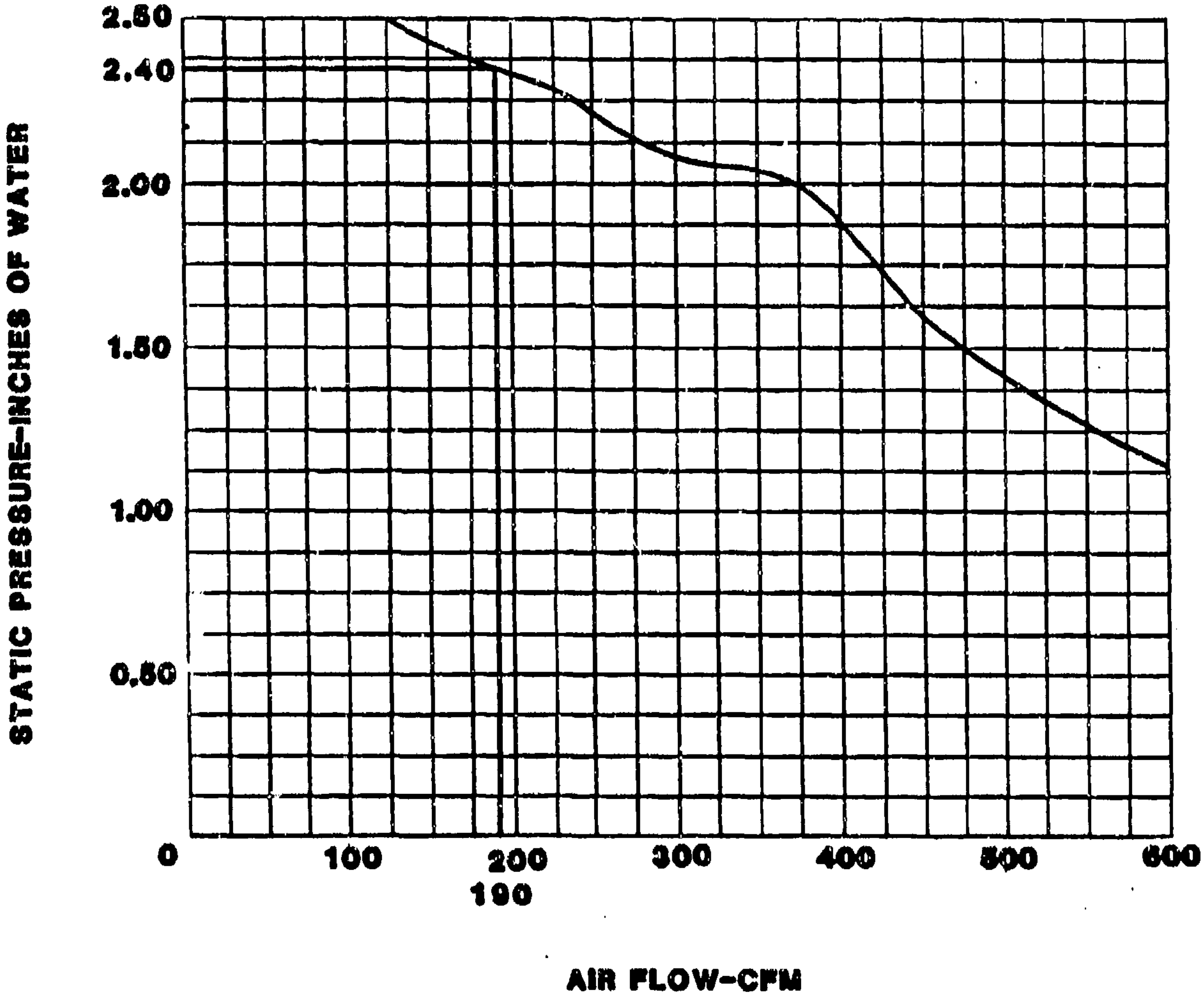
TACOM 7000-28-1

FIGURE 5-2 . FAN SPECIFIC SPEED



NOTE: FIGURE BASED ON DATA FOUND IN.[60] TACOM 7000-29-1

FIGURE 5-29. COMBUSTION AIR BLOWER PERFORMANCE



NOTE: FIGURE BASED ON DATA FOUND IN [61]

TACOM 7000-30-1

FIGURE 5-30. AIR CIRCULATING FAN PERFORMANCE

The motor shaft horsepower (SHP)[59] is defined as:

$$SHP = \frac{AHP}{e_F},$$

with e_F the fan efficiency.

The SHP's for both fans are added together, and then the motor input horsepower (IHP)[59] is:

$$IHP = \frac{SHP_E + SHP_B}{e_M},$$

where:

SHP_F = SHP of air circulation fan,
SHP_B = SHP of combustion air blower,
e_M = motor efficiency.

Multiplying the IHP by 746 W/HP gives the electrical power in Watts.

Table 5-11 shows the possible range of the electrical power for the combined unit. It is estimated that the fans will operate near the peak point.

The fan drive motor is operated directly from the TEC output voltage at 12 VDC nominal. This method of air delivery is self-controlling for both circulated air and combustion air. The personnel heater can be used to illustrate how this self control is accomplished.

When the temperature of the ambient air is very cold, the fuel control system will deliver maximum fuel to the burner. As a result, the TEC combustion temperatures will be maximized, which increases the temperature difference across the TEC. Furthermore, the circulating air will be very cold and cause an even larger temperature difference across the TEC. From par. 5.2.2.1., it was explained that larger temperature differences will increase the TEC voltage. With all these factors combined, the net result is that at cold ambient temperatures, maximum TEC power is generated and maximum heat is produced due to the increased fuel flow and air delivery rates.

Inversely, at high ambient temperatures, the temperature drop across the converter will be reduced, causing less TEC power to be generated. As a result, air flow delivery is lowered and less heat is released by the system.

This self-governing feature is dictated by fuel modulation according to ambient temperature, and the effect of ambient temperature on the TEC cooling. Consequently, the heat output and combustion control are modulated by the TEC's own characteristics and the ambient temperature. The

Table 5-11. Combustion Air Blower and Air Circulation Fan Electrical Power

		Typical		Peak	
	Air Power* (W)	Fan Efficiency (%)	Motor Shaft Power* (W)	Fan Efficiency (%)	Motor Shaft Power* (W)
Combustion Air Blower	12.7	30	42.3	45	28.2
Air Circulation Fan	24.6	30	82.0	38	64.7
Total Shaft Power	--	--	124.3	--	92.9
Motor Input Power**			194.2		145.2

* Horsepower X 746

** Motor Efficiency = 64% (estimated)

References = 59, 62

simplicity of this type of control makes the heater control reliable and affordable.

At start-up, the combustion air flow will be restricted by an electrically-operated solenoid valve (see pars. 5.9.3. and 5.9.5.) that will move to normally open once combustion has been stabilized. At the same time, the drive motor will take its power from the external starting battery, which is at 4 VDC (after being stepped down from 28 VDC by a DC/DC voltage converter). This converter will be bypassed as the voltage produced by the thermoelectric converter (TEC) becomes greater than 4 VDC. The motor voltage will increase as the TEC output rises to 12 VDC. At this point, both fans will be functioning at full capacity.

A corresponding behaviour occurs with the burner. During start-up, a minimum of combustion air must be delivered as it is essential that the flame not be extinguished due to excessive air. As stable combustion is established, more air can be delivered. As the amount of available air increases, the combustion chamber wall temperature will decrease as the heat is carried away by the added thermal mass. This contributes to the maintenance of the temperature difference across the converter.

5.9.11. Portable Heater Fuel Tank. It is required that the portable heater have its own fuel supply, sufficient for one hour's operation. For this purpose, a detachable fuel tank has been designed, and is shown in Figure 5-31.

Its estimated volume will be about 180 in^3, which corresponds to approximately 5.5 lb of fuel. Prior to use, the tank will be pressurized by a small hand pump similar to ones utilized in portable camping stoves. After use, this pressure will be released by slowly opening the fill cap.

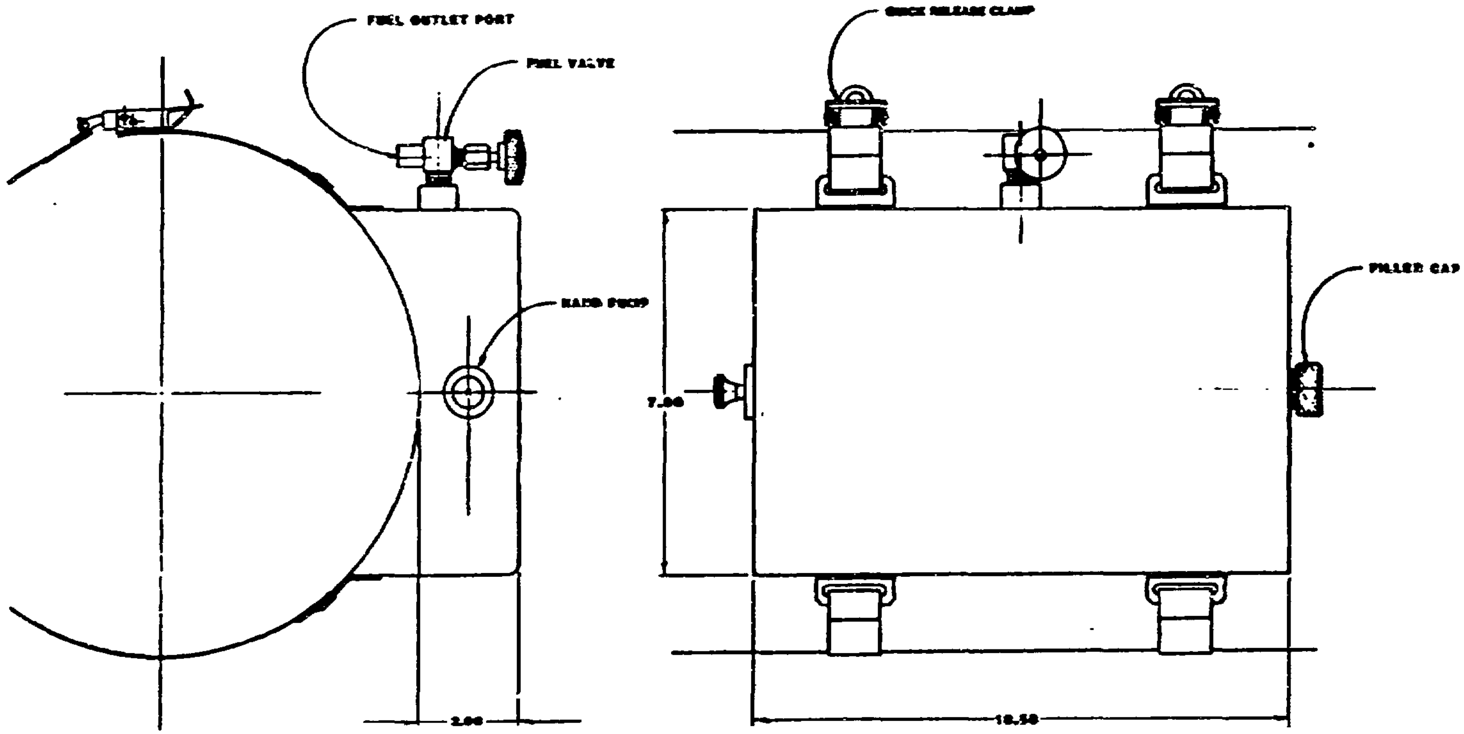
The fuel flow rate and fuel line pressure will be controlled by the fuel valve. The fuel line will be a flexible metal hose and shall be connected to the regulator by means of a quick-release fitting.

The tank will be strapped to the outer shell of the HPM and held in place by a quick-release latch.

5.10. Heater Assembly

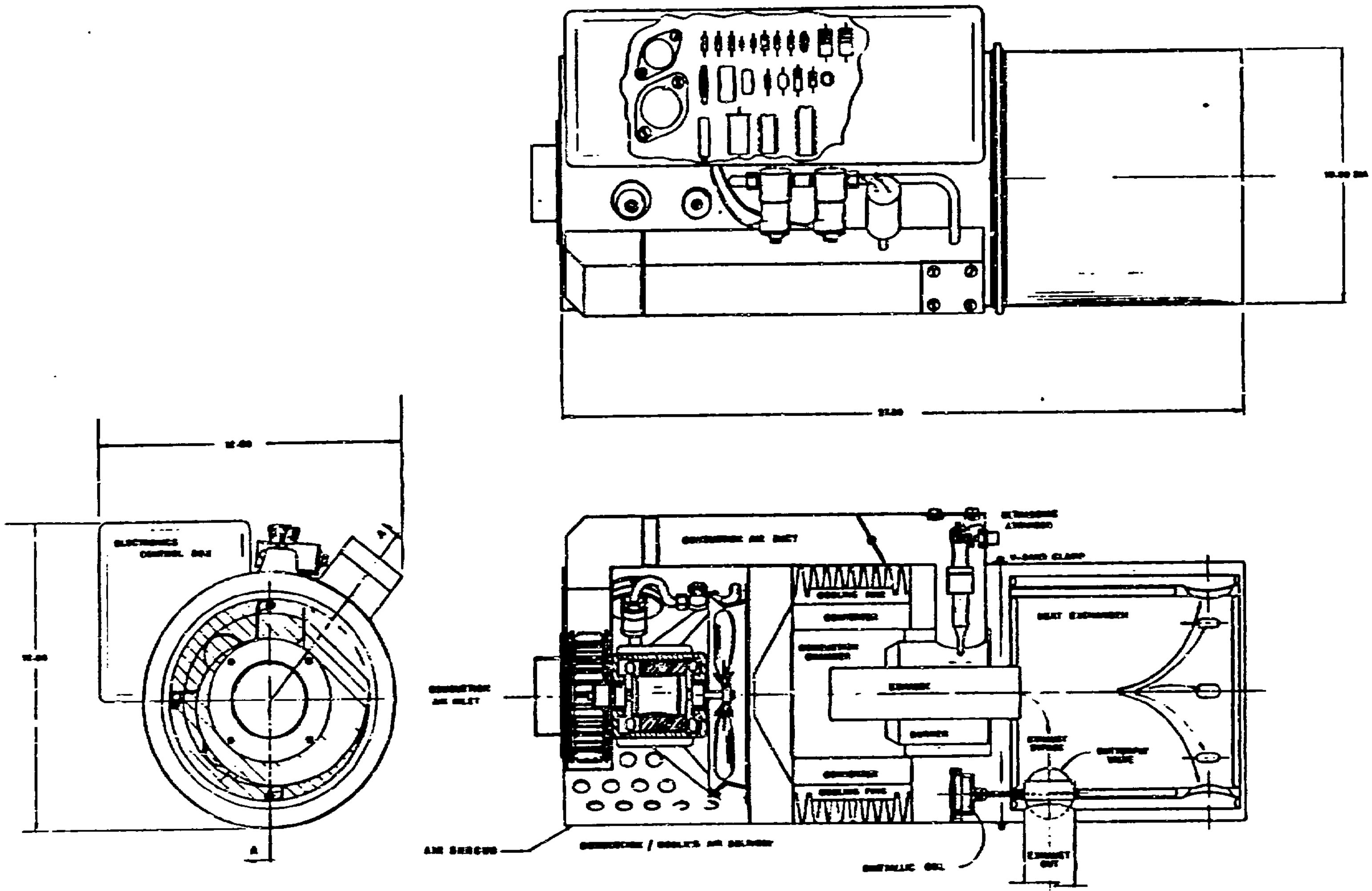
5.10.1. General. Figure 5-32 shows a sectional view of the personnel heater when fully assembled. Figure 5-33 is an exploded isometric projection of the same unit. All the major subsystems have been described in pars. 5.9.1. to 5.9.7. and 5.9.10. The following is a description of aspects pertaining to the final assembly which had not been previously addressed. A component list for Figure 5-33 is given on Table 5-12.

5.10.2. Component Lifetime. It is required that the heater have a mean time between failures of at least 1,000 hours. All components and subsystems shall be designed or obtained so that when installed, a complete heater will meet this 1,000 hr minimum.



TACOM 7000-31-3

FIGURE 5-31. PORTABLE HEATER FUEL TANK



TACOM 7000-32-4

SECTION A-A

FIGURE 5-32. HEATER SECTIONAL VIEW (PERSONNEL HEATER)

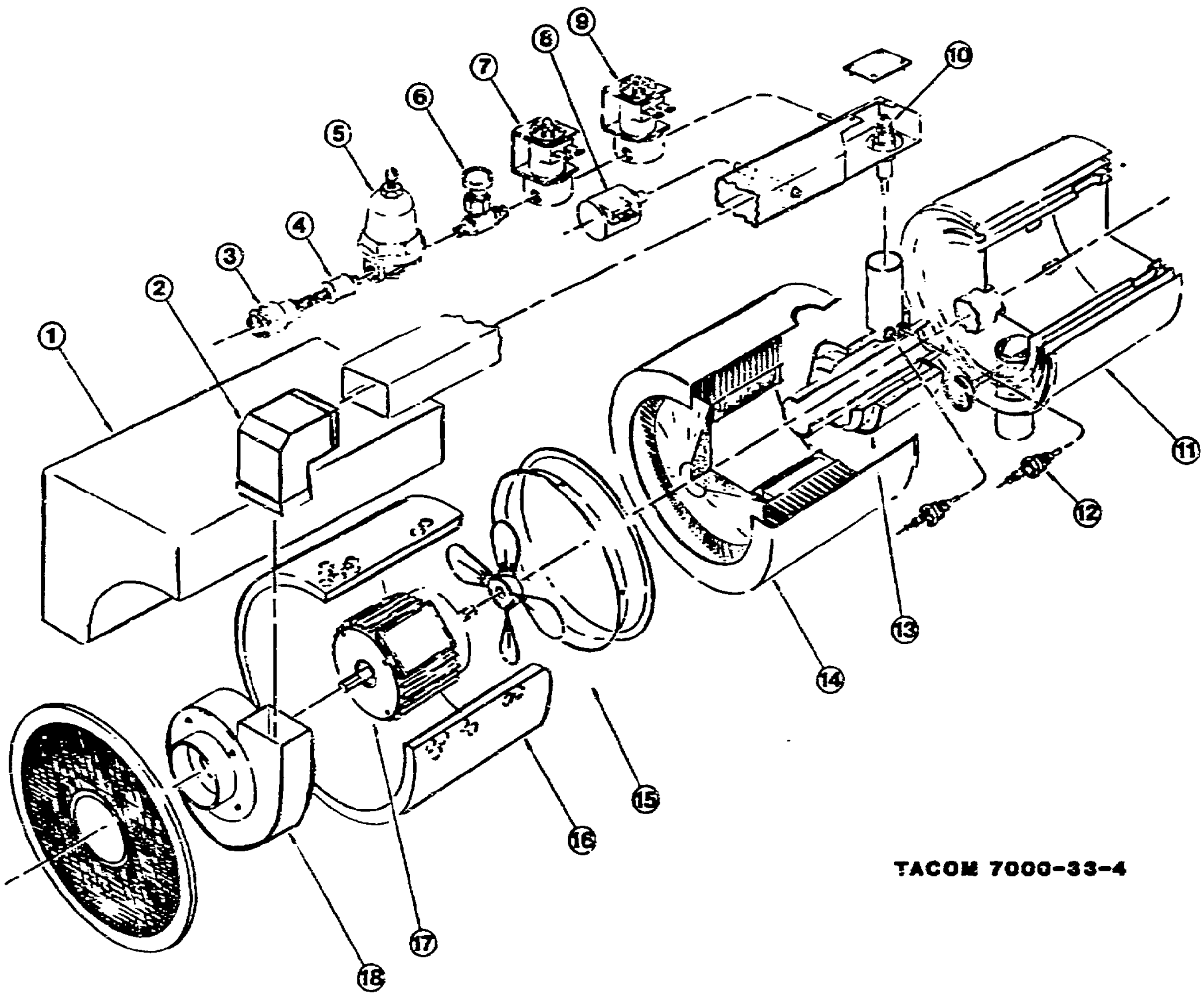


FIGURE 5-33. HEATER ISOMETRIC VIEW (PERSONNEL HEATER)

Table 5-12. Personnel Heater Component List

Item	Description	Also Shown On Figure
1	Electronics Control Box	5-32
2	Combustion Air Delivery Duct	5-32
3	Quick Connect Fuel Coupling	5-17
4	Fuel Filter	5-17
5	Fuel Pressure Regulator	5-17
6	Temperature Actuated Needle Valve	5-17
7	Primary Fuel Solenoid Valve (Normally Closed)	5-17
8	Combustion Air Choke Solenoid Valve (Normally Open)	5-32
9	Secondary Fuel Solenoid Valve (Normally Open)	5-17
10	Ultrasonic Atomizer	5-14
11	Heat Exchanger (Personnel)	5-23
12	Spark Plug	5-16
13	Liquid Multifuel Burner	5-16
14	Thermoelectric Converter	5-8
15	Air Circulation Fan	5-27
16	Air Shroud	5-32
17	Electric Motor	5-27
18	Combustion Air Blower	5-27

5.10.3. Acoustic Noise and Electromagnetic Interference. The heater shall be designed to emit as little acoustic and electromagnetic noise as possible. It shall be constructed with acoustic insulation and electromagnetic shielding to reduce these emissions, if required. The heater shall be tested for compliance with the requirements of MIL-STD-1474B (Acoustic Noise) and MIL-STD-461B and MIL-STD-462 (Electromagnetic Interference).

5.10.4. Shock and Vibration. The heater shall be designed and constructed to withstand the anticipated shock and vibration loads of field conditions. All joints and seals shall remain leak-tight during exposure to the associated forces. All components will be built on that basis. The entire heater shall be tested for compliance with the requirements of MIL-STD-810.

5.10.5. Weight. The heat and power module when connected to any given heat exchanger shall weigh less than 40 lb.

5.10.6. Heater Finish. All surfaces shall be smooth and all sharp and/or jagged edges shall be rounded. The heater exterior shall have a standard military finish in olive green, and all electronic components shall be coated. All finished surfaces and components shall be resistant to salt, dust, sand, humidity, chemical agents, and decontamination solutions.

5.10.7. Safety. All exposed heated surfaces will be either insulated or be isolated by safety guards. All exposed moving parts shall also be isolated by guards.

5.10.8. Maintainability. As far as possible, the heater is designed to be maintained with standard screwdrivers, wrenches, and pliers, with all major components readily accessible. As described in par. 5.9.7., the heat and power module (HPM) shall be connected to an exchanger by means of a quick-release V-band clamp which can be opened and removed by hand without any tools being required.

5.10.9. NBC Operation. It is required that the combustion air supply be independent of that for personnel ventilation. For that purpose, a connection on the inlet to the combustion air blower has been provided to facilitate attachment to the existing vehicle ducting.

5.11 Theoretical Heater Performance

5.11.1. Heat and Power Module. Table 5-13 shows a summary of a number of operating characteristics for the heat and power module. It incorporates several points from the technical requirements paragraphs and from performance calculations completed during the design phase of the contract.

5.11.2. Personnel Heater. Table 5-14 shows a summary of several operating characteristics for the personnel heater, both required and estimated.

Table 5-13. Heat and Power Module Performance

	Required	Estimated
• Heat and Power Module		
Total Available Heat Rate (BTU/hr)	100,000	---
Exchanger Heat Delivery Rate (BTU/hr)	---	87,440
Heat-To-Power Conversion Rate (BTU/hr)	---	1,035
Heat Recovery Rate (BTU/hr)	---	11,525
Gross Electrical Power Produced (W)	---	300
Net External Electrical Power Available (W)	---	50
Fuel Consumption Rate (lb/hr)	4.8 - 5.0	5.0
• Thermoelectric Converter		
Hot Side Temperature (°F)	---	1,145
Cold Side Temperature (°F)	---	245
Leg Efficiency (%)	---	8.25
Input Heat Rate (BTU/hr)	---	12,560

Table 5-14. Personnel Heater Performance

	Required	Estimated
• Personnel Heater		
Heat Delivery Rate (BTU/hr)	60,000	60,000
Discharge Heat Temperature (°F)	280±20	329*
Discharge Pressure (in. water)	1.3	1.3
Discharge Flow Rate (SCFM)	190.0	190.0
• Air Side (Heat Exchanger)		
Heat Recovery Rate From Thermoelectric Converter (BTU/hr)	---	11,525
Cooling Air Flow Rate (SCFM)	---	190
Exchanger Inlet Temperature (°F)	---	112*
Exchanger Outlet Temperature (°F)	---	329*
• Exhaust Side (Heat Exchanger)		
Heat Transfer Rate (BTU/hr)	---	48,475
Exhaust Flow Rate (lb/hr)	---	259
Exchanger Inlet Temperature (°F)	---	1300-1350
Exchanger Outlet Temperature (°F)	---	650-675
Available Heat (BTU/hr)	---	87,440
Heat Transfer Area (ft^2)	---	6

* Based on 60°F ambient

5.11.3. Coolant Heater. Table 5-15 shows a summary of some operating characteristics for the coolant preheater, accounting for both those required and calculated.

5.11.4. Portable Heater. Table 5-16 shows a summary of a number of operating characteristics for the portable heater, including those given in the technical requirements paragraphs and those obtained by calculation.

5.12. Cost Estimate

Table 5-17 shows the anticipated costs for the heater system in a production run of 10,000 military quality units.

These figures are expressed in terms of 1986 United States dollars. As far as possible, the costs were determined in terms of Canadian funds and converted into the equivalent American prices using an anticipated exchange rate of $1.37 Canadian per $1.00 American (as of May 31, 1986).

The costs were based on fabrication or purchase of 10,000 units. It was assumed that the heaters would be manufactured in batch lots, using automation and assembly line techniques where possible. Such large amounts make possible a number of cost reduction methods, such as die-casting the thermoelectric converter follower blocks (see par. 5.9.1.3.) and burner components (see par. 5.9.4.) with minor machining required for finishing. Discounts on components purchased from outside suppliers are also possible, though this will vary from one item to another.

Not presented in this cost estimate is the Mass Producible Converter design. Development of this concept could cut the thermoelectric cost by 80 percent (see par. 5.9.1.4.). Although this concept cannot be presented in this study, it can be easily retrofitted when it is ready for commercial application.

Table 5-15. Coolant Heater Performance

	Required	Estimated
• Coolant Heater		
Heat Delivery Rate (BTU/hr)	30,000	30,000
Discharge Heat Temperature (°F)	190	190
Discharge Pressure (psig)	10	10
Discharge Flow Rate (USGPH)	80-100	90
• Coolant Side (Heat Exchanger)		
Initial Coolant Temperature (°F)	---	-65
Final Coolant Temperature (°F)	---	190
Temperature Rise (°F)	---	41*
Mixture (% Volume)	---	68 (Glycol) 32 (Water)
• Exhaust Side (Heat Exchanger)		
Heat Transfer Rate (BTU/hr)	---	30,000
Exhaust Flow Rate (lb/hr)	---	259
Exchanger Inlet Temperature (°F)	---	1300-1350
Exchanger Outlet Temperature (°F)	---	900-925
Available Heat (BTU/hr)	---	87,440
Heat Transfer Area (ft^2)	---	6

* Based on 190°F outlet temperature

Table 5-16. Portable Heater Performance

	Required	Estimated
Heat Delivery Rate (BTU/hr)	40,000	98,965*
Discharge Flow Rate (SCFM)	200	244
Discharge Temperature (°F)	212	400-425
Exhaust Composition (% Weight)	---	1.4 CO_2
	---	0.5 H_2O
	---	1.1 Ar
	---	75.4 N_2
	---	21.6 O_2

* Total of heat recovered from thermoelectric converter and combustion chamber.

Table 5-17. Heater Cost Analysis

Subsystem	Price (1986 $US)*	
• Heat and Power Module		
Thermoelectric Converter	2160.00	(1250.00)**
Combustion Air Blower and Circulating Air Fan	450.00	
Ultrasonic Atomizer	170.00	
Ignition	35.00	
Electronics	1285.00	
Fuel Regulation and Control	260.00	
Shell	125.00	
Final Assembly	90.00	
Subtotal	$4575.00	($3665.00)**
• Personnel Heat Exchanger		
Burner	120.00	
Exchanger	350.00	
Exhaust Bypass	80.00	
Final Assembly	20.00	
Subtotal	$570.00	
• Coolant Heat Exchanger		
Burner	120.00	
Exchanger	350.00	
Exhaust Bypass	80.00	
Coolant Pump	50.00	
Final Assembly	170.00	
Subtotal	$770.00	
• Portable Heat Exchanger		
Burner	120.00	
Exchanger	80.00	
Fuel Tank	80.00	
Subtotal	$280.00	

* Prices listed are estimates based on quantities of 10,000.

** Revised HPM price estimate dependent on MPC technology applied to the thermoelectric converter.

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GLOSSARY

TERMS, ACRONYMS, AND DEFINITIONS

Air Horsepower	Mechanical horsepower delivered to the air by a fan.
Circulating Air	Air drawn into the heater by the circulating air fan (i.e., axial) and used for cooling the thermoelectric converter. It is also used for heating by the personnel and portable heaters, receiving heat from the thermoelectric converter and the heat exchanger.
Combustion Air	Air drawn into the liquid multifuel burner by the combustion air blower (i.e., centrifugal), mixed with atomized liquid fuel, and ignited. Heat from the resulting exhaust is transferred to the circulating air in the heat exchanger.
DEC	Direct Energy Converter, a means of producing electrical power from heat without any intermediate stages or processes.
Manprint	Specifications covering personnel safety, training, and equipment operation.
Motor Input Horsepower	Electrical horsepower required by fan drive motor.
HPM	Heat and Power Module, the interchangeable segment of the heater which produces the electrical power for self-sustained operation and 100,000 BTU/hr of available heat.
Heater	An operating system consisting of the HPM attached to a heat exchanger.
Heat Exchanger	The segment of the heater which transfers heat from the liquid multifuel burner exhaust to either air which has been circulated through the thermoelectric converter cooling fins or the vehicle engine coolant.
Motor Shaft Horsepower	Mechanical horsepower delivered by fan drive motor to fan.
TEC	ThermoElectric Converter, a class of DEC based upon thermoelectric materials.

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APPENDIX

TITLES SELECTED FOR FURTHER EXAMINATION

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During the early stages of the work done under Contract Number DAAE07-85-C-R167, a literature survey was conducted, as mentioned in par. 5.1.2. Several hundred titles relating to direct energy conversion and liquid fuel combustion were found. A number of these were selected for further examination together with titles obtained from other sources, and some were used in this report.

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